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THESIS

EMERGENCY FIRST RESPONSE TO A CRISIS EVENT: A MULTI-AGENT SIMULATION APPROACH

by

Jonathan W. Roginski

June 2006

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13. ABSTRACT (maximum 200 words)

Homeland Security Presidential Directive #8 led to the establishment of the National Exercise Program and the Top Officials exercise series to test and evaluate first response agency integration and effectiveness. The last TOPOFF exercise cost $16M and involved over 10,000 people, but did not effectively leverage simulation techniques to make efficient use of resources.

This research adapts an existing organizational learning process, integrating low- and high resolution simulation to provide decision support. This process led to the development of a multi-agent simulation methodology for emergency first response, specifically applied to analyze a notional vehicle bomb attack during a festival in the Baltimore Inner Harbor.

This simulation demonstrates the potential benefits of low resolution simulation, using efficient experimental design and high-performance computing. Combined, these two ideas result in examining a 48-dimensional response surface and using over 156 CPU centuries of computer time. All experiments were completed in less than three weeks.

The analysis of this data set provided insight into several areas, including the importance of standing operating procedures in the early moments of a crisis. Analysis showed that effective procedures may even be more important than the effectiveness of communications devices early in a first response operation.

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EMERGENCY FIRST RESPONSE TO A CRISIS EVENT: A MULTI-AGENT SIMULATION APPROACH

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AAR	After Action Review
AMSAA	Army Materiel Systems Analysis Activity
CART	Classification and Regression Tree
CEP	Circle Error Probable
CBRNE	Chemical, Biological, Radiological, Nuclear, and Explosive
DHS	Department of Homeland Security
DMSO	Defense Modeling and Simulation Office
DoD	Department of Defense
DOE	Design of Experiments
EMT	Emergency Medical Technician
EPiCS	Emergency Preparedness incident Command System
DHS/ODP	Department of Homeland Security/Office of Domestic Preparedness
FRLH	Flexible Random Latin Hypercube
FSL	Federal, State, and Local
GUI	Graphical User Interface
HSPD	Homeland Security Presidential Directive
ICP	Incident Command Post
IED	Improvised Explosive Device
JANUS	Joint Army Navy Uniform Simulation
Kph	Kilometers Per Hour
MAS	Multi-Agent Simulation
MANA	Map Aware Nonuniform Automata
MHPCC	Maui High Performance Computing Center
MOE	Measure of Effectiveness
MOP	Measure of Performance
MS&G	Models, Simulations, and Games
MTRY	Monterey, as in TRAC-MTRY
NEP	National Exercise Program

NIMS	National Incident Management System
NOLH	Nearly Orthogonal Latin Hypercube
NPG	National Preparedness Goal
NRP	National Response Plan
ODP	Office for Domestic Preparedness
OLH	Orthogonal Latin Hypercube
PAIW	Project Albert International Workshop
P_k	Probability of Kill
ROE	Rules of Engagement
SLGCP	Office of State and Local Government Coordination and Preparedness
SME	Subject Matter Expert
SOP	Standing Operating Procedures
SSPK	Single Shot Probability of Kill
SWAT	Special Weapons And Tactics
TOPOFF	Top Officials, pertaining to the Top Official Exercise Program
TRAC	Training and Doctrine Command Analysis Center
TTPs	Tactics, Techniques, and Procedures
U.S.	United States
VBIED	Vehicle-Borne Improved Explosive Device
WG	Wargame(ing)
WMD	Weapon of Mass Destruction
WSMR	White Sands Missile Range, as in TRAC-WSMR
XML	Extensible Markup Language

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Dian, words just do not express the gratitude I feel for your support in this entire process. It would have been simply impossible for me to complete this work without your strength and sense of humor. Thank you for taking care of business on the home front and keeping our girls safe and happy. Carleigh, thank you for your hugs and smiles and making Daddy feel special when he finally comes home. Kathryn, thank you for your wonderful smile and your giggles, and the happiness in your eyes when our whole family is together.

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EXECUTIVE SUMMARY

Large-scale disasters can quickly overwhelm the capabilities of state and local governments. An effective response in these situations results from integrating state and local agencies with their federal counterparts, thus enabling the flow of needed resources and knowledge. Toward this end, a Presidential Directive was issued as part of a plan to prepare for and mitigate the effects of crisis events. This directive led to the establishment of the National Exercise Program (NEP). National-level exercises, such as those that comprise the NEP, test and evaluate federal, state, and local (FSL) integration and readiness to confront a manmade or natural disaster.

Top Officials (TOPOFF) exercises are the foundation of the NEP. These large-scale exercises involve participation from all levels of governmental and nongovernmental agencies inside and outside the United States. These exercises are currently being planned and executed with very little consideration given to the value of simulation as a preparation tool.

Simulation is a widely used decision support tool because it allows staffs and decision makers to explore given problems in ways that are otherwise impractical (e.g., due to resources needed) or impossible (e.g., running an exercise with thousands of parameter permutations). The Department of Homeland Security (DHS) recognizes the value of simulation and reviews simulation models for applicability before each TOPOFF planning process begins. As yet, DHS has not found the right tool for the job.

Figure ES1 demonstrates an organizational learning process adapted from a methodology developed by the U.S. Army Training and Doctrine Command Analysis Center – Monterey (TRAC-MTRY); *this* is the right tool for the job. This methodology is an iterative process that uses a quick turnaround, low resolution model to provide initial insights into a given problem. Those insights are used in the execution of a high resolution simulation, such as a wargame. As with any high resolution simulation, wargaming results can be actionable results; that is, the decision maker can use these results to finalize the plan that was wargamed. However, the decision maker can also decide to adjust the low resolution simulation and iterate the process until they obtain satisfactory results.

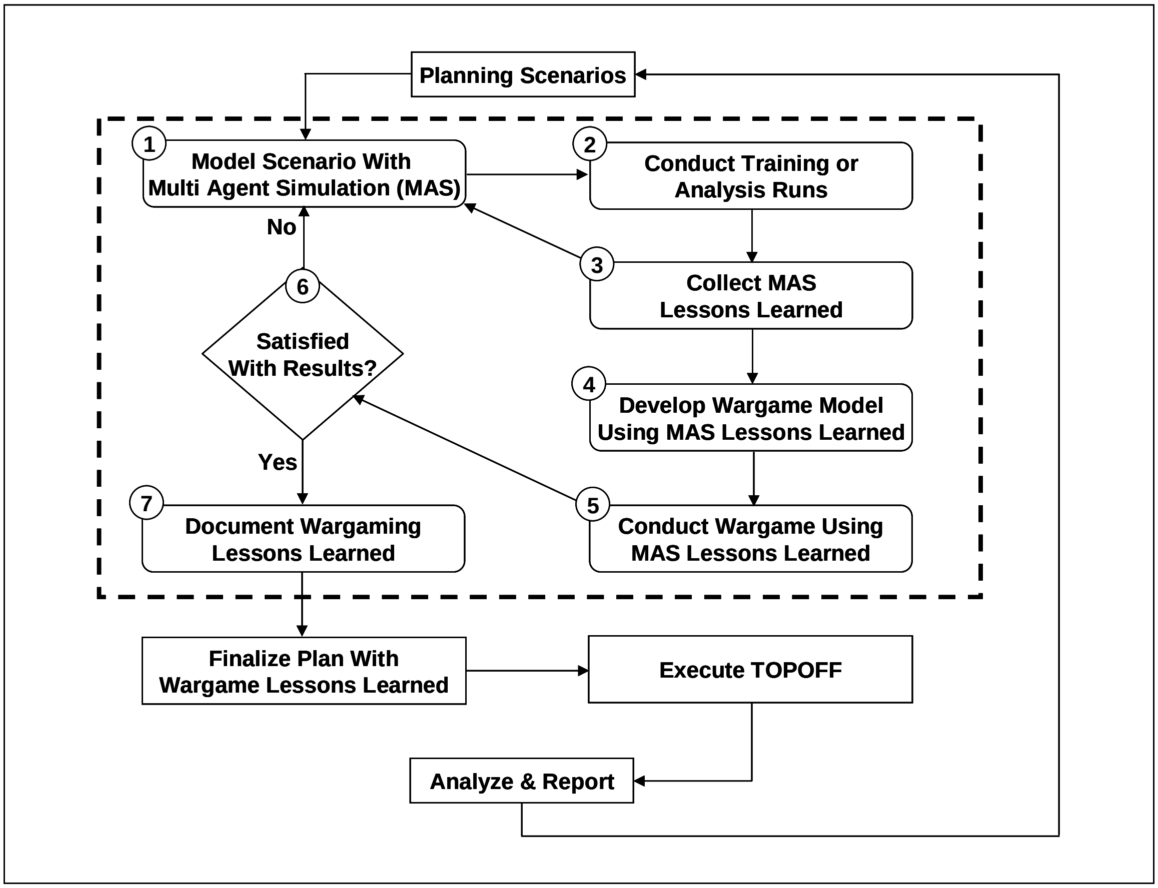

Figure ES1. Adaptation of TRAC-MTRY's Learning Methodology

The process established in this research expands the TRAC-MTRY methodology, which includes a general flow that uses the power of simulation to train a given audience. This research shows a specific process by which low resolution and high resolution simulation can be used together to help organizations prepare for a TOPOFF exercise, or any other large-scale training exercise.

High-resolution simulations, such as wargames, are established decision support tools. TRAC-White Sands Missile Range (WSMR) developed a model to facilitate the execution of wargames in a first-response setting. The

Emergency Preparedness incident Command System (EPiCS) was used in February 2006 to simulate emergency first response to a bomb attack in Baltimore's Inner Harbor area, during a festival. To assess and demonstrate the potential of an agile, low resolution simulation in this methodology, a multi-agent simulation (MAS) was developed to simulate the same vignette. The simulation involves a small terrorist cell that detonates a car bomb, then works to further incite panic, while a gunman lies in wait for first responders to attack. Police, fire, and medical personnel respond to the bomb blast area, in which walking wounded and stretcher wounded civilians are panicking. First responders have the following priorities of work, in which police, Emergency Medical Technicians (EMTs), and firemen will:

- Stabilize wounded civilians
- Restore calm in the area
- Eliminate further threats
- Maintain safety of first responders

Figure ES2 is an illustrated screen shot of the emergency first response MAS.

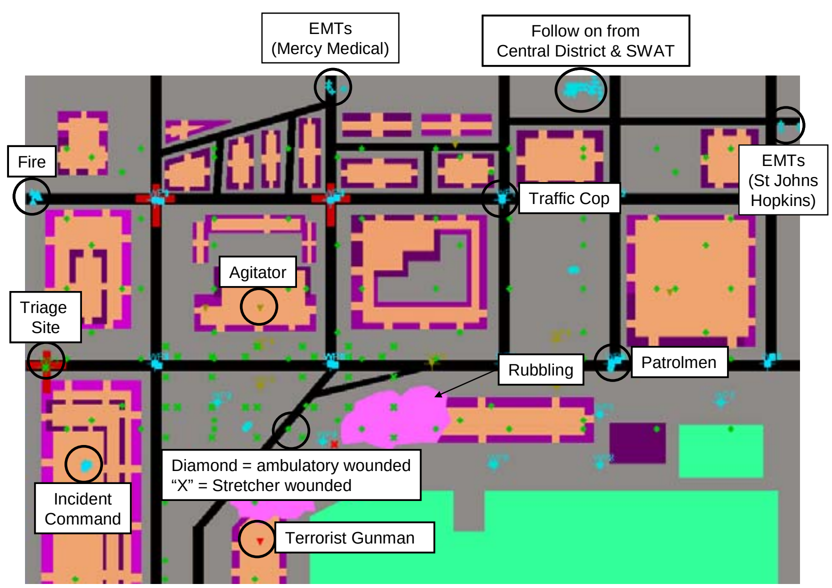

Figure ES2. Screen Shot of Emergency First Response MAS

In the analysis of the first responder effectiveness, this research involved exploring a 48-dimensional space to gain an understanding of the complex relationships involved in this problem. This exploration required an efficient design of experiments. A traditional gridded design would have resulted in experimental runs that lasted 116 trillion times the current age of the universe. The design of experiments developed for this research uses both the flexibility of Flexible Random Latin Hypercube (FRLH) sampling, and the space filling nature of Nearly Orthogonal Latin Hypercube (NOLH) sampling. The use of these efficient designs, in conjunction with use of the supercomputers at the Maui High Performance Computing Center (MHPCC), resulted in the use of 137,277,343 CPU hours, or 156 CPU centuries. The data set analyzed for this research is nearly 52,000 rows by more than 5,300 columns.

The analysis of the data from this model suggest:

- *Overwhelmingly,* the most important factor in achieving success in crisis mitigation is the effectiveness of the police in taking positive control of the crowd, exerting calming influence, and providing direction.
- If a police force is not well trained, and therefore not very effective, the officers may achieve greater success by being less persistent with individuals; that is, by spreading their influence more broadly.
- Well established, well executed standing operating procedures (SOPs) may play a more important role in first response operations than interagency communication.
- There may be a level of diminishing returns for first responder training; that is, a person can be only *so* trained. After that level is reached, it may be more effective to leverage resources elsewhere.

Results of the data analysis are not meant to directly apply to actual emergency response techniques, or specifically to the City of Baltimore. This model does not include the actual force structure and SOPs from Baltimore, but data adapted from the February 2006 EPiCS run. This research is a proof of concept to show that it is possible to quickly and credibly model emergency first response with a MAS, and the data analysis from such a credible, verified, and calibrated model will be useful and insightful.

The single most important result of this research comes not from the data analysis, but from the developed methodologies. Simulation is a decision support technique that is relevant to emergency preparedness, especially to an exercise program the size and complexity of the TOPOFF program. The organizational learning technique discussed herein and the incorporation of MAS in emergency first response simulation can help train first response organizations more effectively, resulting in better crisis mitigation and lives saved.

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I. INTRODUCTION

> Our Federal, State, and local governments would ensure that all response personnel and organizations—including law enforcement, military, emergency response, health care, public works, and environmental communities—are properly equipped, trained, and exercised to respond to all terrorist threats and attacks in the United States.[1]
>
> National Strategy for Homeland Security
> July 2002

A. NATIONAL EXERCISE PROGRAM BACKGROUND

The President issued Homeland Security Presidential Directive Number 8 (HSPD-8, Subject: National Preparedness) as part of a plan to prepare for and mitigate the effects of crisis events. In HSPD-8, the President directed the Secretary of the Department of Homeland Security (DHS) to

> . . . establish a national program and a multi-year planning system to conduct homeland security preparedness-related exercises that reinforces identified training standards, provides for evaluation of readiness, and supports the national preparedness goal.[2]

This presidential directive led to the establishment of the National Exercise Program (NEP). National-level exercises, such as those that comprise the NEP, evaluate federal, state, and local (FSL) integration and test "collective preparedness, interoperability, and collaboration across all levels of government and the private sector."[3]

State and local preparedness is necessary, but insufficient, for effective disaster response, as large-scale disasters can quickly overwhelm the

[1]*Homeland Security Exercise and Evaluation Program, Volume I: Overview and Doctrine*, revised May 2004, p. 4. Retrieved on 26 January 2006 from the World Wide Web at http://www.ojp.usdoj.gov/odp

[2]"Homeland Security Presidential Directive #8." Retrieved on 5 December 2005 from the World Wide Web at http://www.whitehouse.gov/news/releases/2003/12/20031217-6.html

[3]Ibid.

capabilities of state and local governments. Effective response in these situations results from integrating state and local agencies with their federal counterparts, thus enabling the flow of needed resources and knowledge.

The NEP is one component of the DHS's endeavor to achieve the National Preparedness Goal (NPG), established by HSPD-8. The NPG "envisions a national system in which all agencies have the capabilities they need to effectively communicate and coordinate resources."[4] The following seven measurable priorities quantify the level of FSL preparedness and achievement of the NPG.

Overarching Priorities. Three NPG priorities contribute to the development of several capabilities:

- Implement the National Incident Management System (NIMS) and National Response Plan (NRP)
- Expand regional collaboration
- Implement the Interim National Infrastructure Protection Plan

Capability-Specific Priorities. Four NPG priorities are capability-specific, providing specific means that the nation needs most:

- Strengthen information sharing and collaboration capabilities
- Strengthen interoperable communications capabilities
- Strengthen chemical, biological, radiological, nuclear, and explosive (CBRNE) detection, response, and decontamination capabilities
- Strengthen medical surge and prophylaxis capabilities to enable emergency-ready public health and medical facilities across the nation[5]

Four of the seven NPG priorities address the need for efficient and effective command and control, communication, and resource sharing in crisis events. The NEP established the Top Officials (TOPOFF) exercise as their

[4]"Fact Sheet: The National Priorities," Department of Homeland Security. Retrieved on 5 December 2005 from the World Wide Web at http://www.ojp.usdoj.gov/odp/docs/Priorities_041305.pdf

[5]Ibid.

cornerstone event to assess the progress of DHS in meeting its NPG priorities.

TOPOFF is a biennial series of exercises mandated by Congress to strengthen the nation's crisis response.[6] These exercises have grown in size and scope since the first one in 2000. TOPOFF 2000 was a $3.5 million national event, incorporating "numerous" FSL agencies.[7] TOPOFF 3, the most recent exercise, was a $16 million *international* event with over 200 FSL agencies and 10,000 participants.[8] The resources dedicated to this exercise series help demonstrate the importance of this program and its role in developing crisis response capabilities. This research will support the TOPOFF program by helping the exercise planning and execution process mature to more efficiently and effectively meet the NPG.

B. SIMULATION AS A TOPOFF FACILITATOR

> *Simulation is one of the most widely used operations research and management science techniques, if not* the *most widely used.*[9]
>
> Law and Kelton, 2000

Simulation is a widely used decision support tool because it enables an organization's staff to efficiently examine problems that would otherwise be expensive to analyze. The staff presents its recommendation to the decision maker based on analysis of the simulation. For example, suppose a

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[6]Department of Homeland Security, "National Exercise Program Overview," Office for Domestic Preparedness. Retrieved on 1 December 2005 from the World Wide Web at http://www.ojp.usdoj.gov/odp/exercises.htm

[7]U.S. National Response Team, "Exercise TOPOFF 2000 and National Capital Region After Action Report," 2001. Retrieved on 5 December 2005 from the World Wide Web at http://www.nrt.org/Production/NRT/NRTWeb.nsf/PagesByLevelCat/Level3TOPOFF?Opendocument

[8]Department of Homeland Security, Press Room, "TOPOFF 3 Frequently Asked Questions." Retrieved on 2 March 2006 from the World Wide Web at http://www.dhs.gov/dhspublic/interapp/editorial/editorial_0603.xml.

[9]Averill M. Law, and W. David Kelton, *Simulation Modeling and Analysis*, 3rd Edition, 2000, p. 2.

manufacturing company is considering the construction of an extension to one of its plants. The company will not build the extension, track change in profit, then tear down the extension if it results in a net loss. However, the company may conduct a form of simulation to examine the likely change in profit based on the decision to build. Using this analysis, a recommendation is made to the decision maker to build or not to build.[10]

Simulation is also a useful decision support technique for analyzing the execution of contingency plans. The U.S. military frequently wargames its military plans before the execution of the plan. Wargaming is a “human-in-the-loop” simulation. Human-in-the-loop means that people are actually involved, making decisions, throughout the simulation. In wargaming, a plan is analyzed by examining an event in terms of a side’s action, another side’s counteraction, and the first side’s subsequent counteraction, and so on. Through analyzing both the results of the simulation and the process by which those results were achieved, a staff can recommend a plan to the decision maker for approval.

In addition to its usefulness in determining the allocation of resources and analyzing contingency planning, simulations are good training tools. Human-in-the-loop simulations, such as wargames, provide the target audience with a chance to react to situations they may encounter when the actual event occurs. Computer simulations usually run more quickly than human-in-the-loop simulations, and can result in many more iterations being run. These many iterations can provide insightful answers to “what if” questions not able to be answered in a slower-running human-in-the-loop simulation.

The DHS’s Office of State and Local Government Coordination and Preparedness (SLGCP) recognizes the potential value of simulation in preparation for the TOPOFF program. Prior to TOPOFF 3, DHS reviewed 100 models, simulations, and games (MS&G), evaluating their usefulness in preparation for and execution of the exercise. The result of this review was that

[10] Averill M. Law, and W. David Kelton, *Simulation Modeling and Analysis*, 3rd Edition, 2000, p. 1.

some MS&Gs proved useful, but "no single group of products can be recommended that will support the requirements of all communities."[11]

The Training and Doctrine Command Analysis Center-Monterey (TRAC-MTRY) is currently studying the use of simulation techniques to facilitate organizational learning. Figure 1 illustrates a methodology proposed by TRAC-MTRY to improve organizational learning, especially in support of the TOPOFF program. This iterative methodology includes scenario planning as the first step. An analyst models the scenario with a high resolution simulation, to be used as a training tool for exercise participants. Data that results from the simulation are analyzed and the base simulation adjusted as necessary to correct modeling deficiencies or perform "what if" analyses. If decision makers are satisfied with the training achieved, the exercise can be executed and results documented.

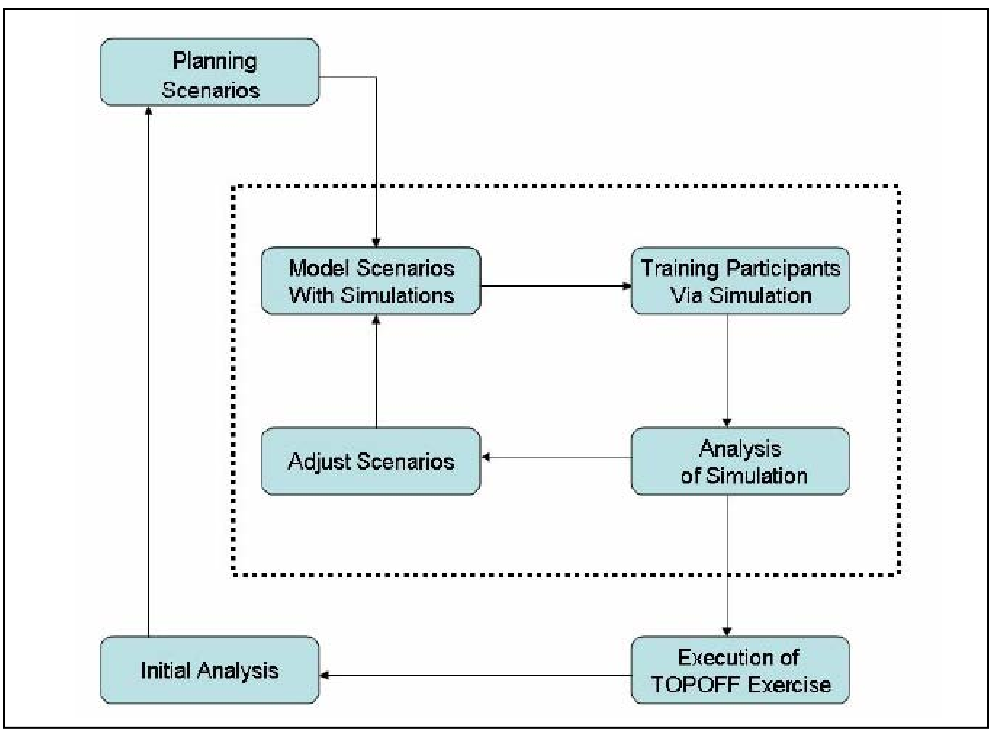

Figure 1. TRAC-MTRY Proposed TOPOFF Methodology to Improve the Learning Process[12]

[11]ThoughtLink, Inc. "Review of Models, Simulations, and Games for Domestic Exercises and Preparedness," (2004). Retrieved on 5 December 2005 from the World Wide Web at http://www.ojp.usdoj.gov/odp/docs/Review_of_MSG_SlimVersion.pdf

Figure 2 illustrates a revised methodology, adapted from the TRAC-MTRY organizational learning methodology. The following paragraphs are numbered in accordance with the steps in this methodology.

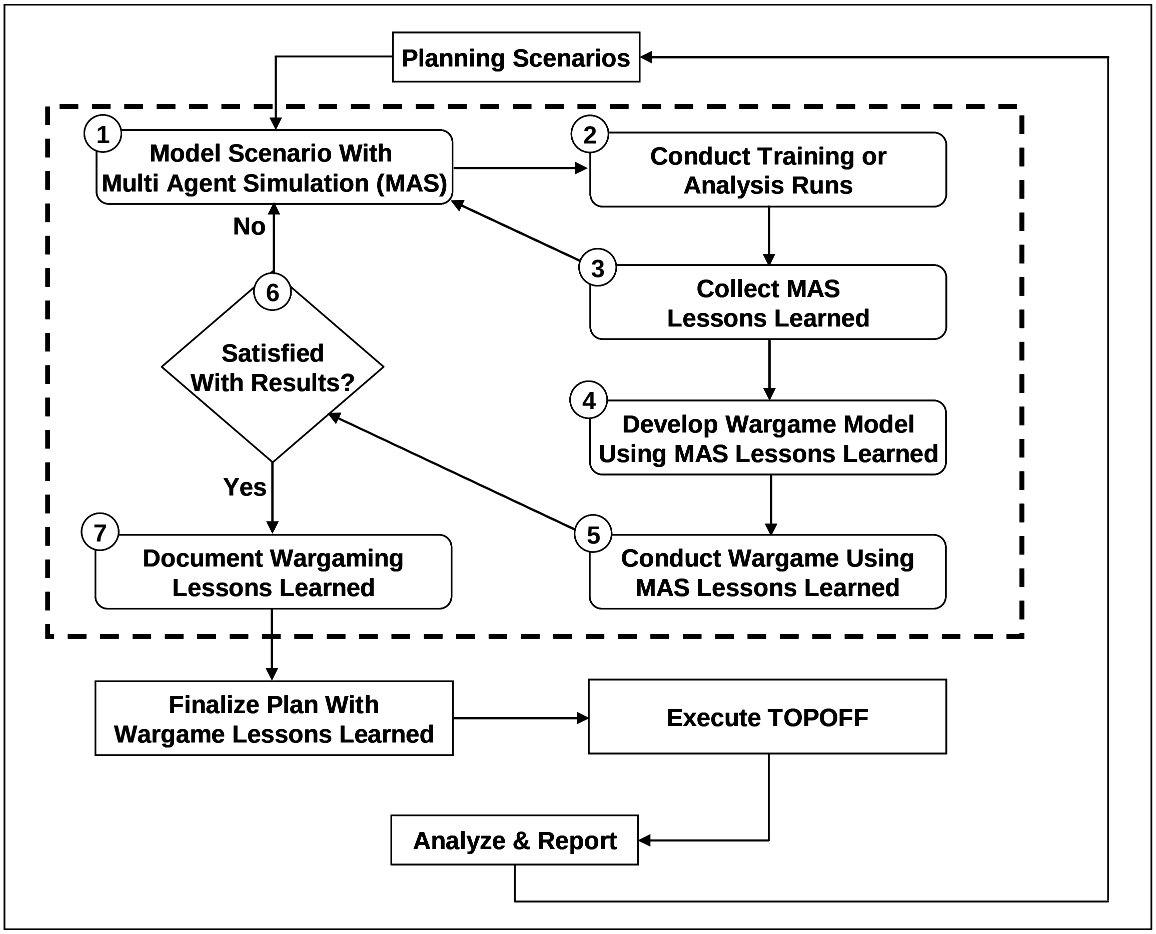

Figure 2. Adaptation of TRAC-MTRY's Learning Methodology[13]

1. Model Scenarios with Multi-Agent Simulation (MAS)

MAS are low resolution models that are (relatively) easy to set up and alter, and are fast to run. Although it is not usually appropriate to use MAS to model an entire TOPOFF exercise, it is useful to model specific vignettes from the exercise plan. The power of MAS is enabled by the use of data farming to

[12] Doris M. Turnage and LTC Jeffrey B. Schamburg, *Facilitating Organizational Learning and Change Through the National Exercise Program*, (December 2005).

[13] Ibid.

thoroughly explore the range of possibilities in these vignettes. The analyst leverages modern computing and supercomputing power to vary parameters and run the scenario thousands of times.

2. Conduct Training or Analysis Runs

MAS can be used for a variety of purposes. Within the context of this research, there are two major applications for low resolution simulation. First, the MAS may be used to train leaders and staffs. Inputting the scenario into the model and visualizing the events that unfold during a given model run can help to validate and streamline procedures. Second, data collection and the subsequent analysis can provide decision makers with insight into "what if" questions that would be difficult to answer in another setting.

3. Collect MAS Lessons Learned

The data farming approach to analysis leads to a much more thorough exploration of the solution space than more complex, slower-running, high resolution models. By understanding the solution space's "landscape," we are able to consider "what if" questions and gain unique insight into the problem.[14] Analysts may use the insights gained from output analysis in two possible ways. The output may indicate a need to refine the MAS scenario, or rerun the experimental design to focus on a certain area. Alternatively, if the analyst is satisfied with the results of the data analysis, the insights are captured as lessons learned. The lessons learned from the low resolution simulation are used as a starting point for a high resolution simulation, such as a wargame simulation.

4. Develop Wargame Model Using MAS Lessons Learned

MAS lessons learned can help provide insight into making necessary assumptions as the model is developed. During the execution of the

[14]LTC Thomas M. Cioppa, "A Potential Role of Agent Based Models in Military Analysis," Information Paper, (prepared December 2003).

human-in-the-loop wargame, MAS lessons learned can assist decision makers in making effective, timely decisions.

5. Conduct Wargame Incorporating MAS Lessons Learned

The wargame can be either a timestep simulation or event-driven. Common to both approaches is that one side will act, the other will react, and the first side will then counteract, and then move to the next timestep or event. This type of simulation is high resolution, meaning that the output is more representative of actual events than the output from a low resolution simulation, and thereby more actionable.[15]

TRAC-White Sands Missile Range (WSMR) developed the Emergency Preparedness incident Command System (EPiCS), which is a computer-based, high resolution simulation. EPiCS is a version of the Joint Army Navy Uniform Simulation (JANUS), a well-known simulation used for many years to facilitate military wargaming. TRAC-WSMR developed EPiCS to facilitate wargaming in emergency response situations requiring multi-echelon and/or interagency communication and coordination.[16]

6. Satisfied With Results?

The decision maker must review the products, insights, and lessons learned from the MAS and wargame. If satisfied that enough insight has been gained by the staff, the decision maker directs the staff to document the lessons learned and finalize the plan. The decision maker may require more information, different information, or a narrowly focused view of a small part of the response surface. In this case, the staff iterates the process of MAS modeling and wargaming.

[15] Defense Modeling and Simulation Office Verification, Validation, and Accreditation Glossary. Retrieved on 20 March 2006 from the World Wide Web at https://www.dmso.mil/public/library/projects/vva/glossary.pdf

[16] EPiCS homepage. Retrieved on 17 May 2006 from the World Wide Web at http://epics.astcorp.com

7. Document Wargaming Lessons Learned

Clearly and concisely documenting the lessons learned from the wargame is as important as running a realistic simulation, and by doing so throughout the simulation process, we can disseminate the information to the people that need it. Wargaming lessons learned may be used in two ways: to refine the original MAS and then begin the process again or to finalize the exercise plan.

Organizational learning does not stop with the final simulation; it continues throughout the TOPOFF exercise, and after. Agency leaders and first responders share the knowledge they gain during the execution of the exercise during "hot wash" after action reviews (AARs). The purpose of these short AARs is to capture important findings before too much time passes and memories fade. Following the TOPOFF exercise, a senior observer leads a comprehensive analysis of the exercise, to gain final insights into strengths and weaknesses of the response. Action facilitated by these insights is the beginning of preparation for the next TOPOFF exercise or next local crisis event.

C. PROBLEM STATEMENT

The SLGCP currently prepares for its biennial TOPOFF exercises without the use of computer simulation (e.g., MAS), and with limited use of human-in-the-loop simulation (e.g., wargaming). Inclusion of simulation in the planning process of TOPOFF exercises could result in increased preparedness, more efficient resource allocation, and more meaningful lessons learned. The goal of this research is to provide a methodology for an analyst to use Pythagoras, or another MAS model, to simulate emergency response to a natural or man-made crisis event. The methodology developed in this thesis can be applied in many different situations, such as a future TOPOFF scenario in a major city, an annual force protection exercise at a military installation, or a small town's response to a flood.

D. SCOPE

This research will focus on the police, fire, and medical response to a small terrorist cell detonating a bomb near the amphitheater in Baltimore's Inner Harbor. This event replicates the event that occurred in exercise TOPOFF 3 in New London, Connecticut. TRAC-WSMR also replicated the New London event within their wargaming simulation, EPiCS. TRAC-WSMR provided the specific scenario and force structure information used in the EPiCS run conducted in February 2006. This MAS development will replicate the first hour of TRAC-WSMR's EPiCS run as closely as possible, using a multi-agent approach.

This work is focused on the following research questions:

- What is an appropriate methodology for use of a MAS environment in the modeling of emergency response to the simulated vehicle-borne improvised explosive device (VBIED) that explodes near the amphitheatre in Baltimore's Inner Harbor?
- What is the most appropriate mix of police, fire, and medical assets?
- What is the most effective interagency communication architecture for emergency response to VBIED in Baltimore's Inner Harbor?

E. THESIS OVERVIEW

The following chapters will provide specific background on the simulation area, details on how the model was constructed, how the data were collected and analyzed, and the resultant conclusions. Chapter II presents detailed information to the reader that addresses the specific scenario analyzed for this research and the organizations included in the model. Chapter III addresses the development and application of a methodology for simulating emergency first response in a multi-agent environment. Chapter IV discusses the implementation of the model in detail, discussing the model's settings, deficiencies, and limitations. Chapter V details the factors that are analyzed and the experimental design methodology. In Chapter VI, the author demonstrates the analysis of data gained from executing the experimental design. The final chapter presents an analysis of the data from the simulation, significant results, and possible follow-on work.

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II. BALTIMORE ATTACK SCENARIO OVERVIEW

This chapter provides the reader with detailed information about the scenario and organizations studied as the basis for this research. The chapter's first section outlines the TOPOFF 3 exercise, the simulated bomb attack, and the reason for moving the location of the simulation to Baltimore from New London for this research. The chapter's second section provides information about the organizations simulated, including force structure and purpose.

A. TOPOFF 3 SCENARIO

The DHS conducted TOPOFF 3 during April 4-8, 2005. This exercise simulated two coordinated terrorist attacks. The first was a pneumonic plague attack in Union and Middlesex counties, New Jersey. The second was a chemical agent release (mustard gas) and high-yield explosive in the City of New London, Connecticut.[17]

The goal of this research is to develop a simulation methodology to model emergency first response in a crisis situation. The methodology must be robust, flexible, and capable of addressing various crisis scenarios in differing geographical settings. The author considered two ways to proceed:

- Develop a detailed simulation and analysis of one vignette
- Develop and analyze several smaller, less detailed vignettes

To create a simulation that is realistic and widely applicable, it is necessary to be detailed in the approach of simulation design and analysis. The detailed approach enables the analyst to answer questions and solve problems that do not surface in a more cursory approach. It is detailed thinking and problem-solving that makes the simulation methodology robust. Therefore, the

[17]Department of Homeland Security, "A Review of the Top Officials 3 Exercise," Office of the Inspector General, Office of Inspections and Special Reviews, p. 4. Retrieved on 25 January 2006 from the World Wide Web at http://www.dhs.gov/interweb/assetlibrary/OIG_06-07_Nov05.pdf

scope of this research is limited to the high-yield explosive attack, which occurs during a festival that draws approximately 10,000 attendees.

The explosion simulated during TOPOFF 3 occurred on April 4, 2005, during the annual Celebrate Connecticut festival held on the New London waterfront. A small terrorist cell, comprised of approximately five personnel, orchestrated a VBIED attack. The VBIED was the equivalent of 7,350 pounds of ammonium nitrate, approximately the same size as the bomb that destroyed the Murrah Federal Office Building in Oklahoma City.[18] Figure 3 illustrates the affected area.

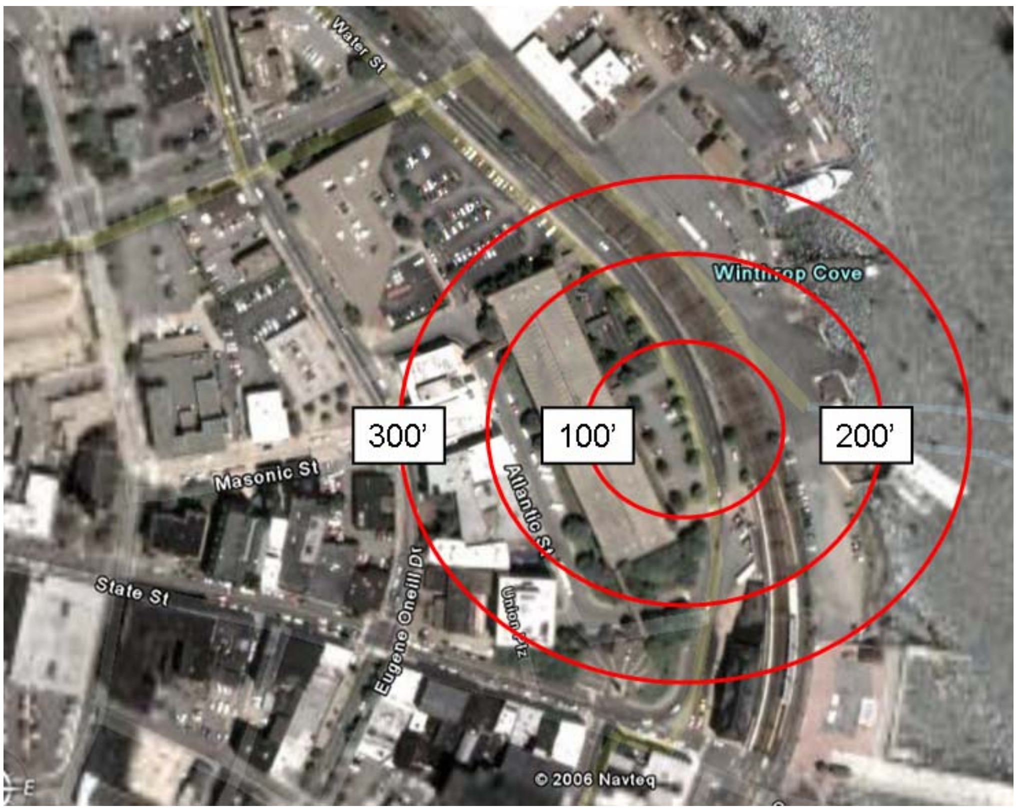

Figure 3. Affected Area of TOPOFF 3 VBIED, New London, CT[19]

[18]E-mail from Dr. Julie Seton, EPiCS Program Manager, TRAC-WSMR, titled "Message from Dan Edmonson – CT Incident Details for TRAC-Monterey Project," 24 January 2006, office communication.

[19]Graphic retrieved on 17 May 2006, Using Google Earth; affected area provided by TOPOFF 3 Full Scale Exercise Final Planning Conference Brief, given March 2-3, 2005. Retrieved on 13 January 2006 from the World Wide Web at http://www.dhs.gov/interweb/assetlibrary/OIG_06-07_Nov05.pdf

B. MOVEMENT OF VIGNETTE TO BALTIMORE

This simulation setting was moved to Baltimore due primarily to funding constraints. The high resolution model chosen for comparison is TRAC-WSMR's EPiCS model. The terrain for Baltimore was available when the EPiCS simulation was built; however, the terrain for New London was not available and would have been both time-consuming and expensive to build.

Movement of the event from its original venue does not decrease this research's relevance. Certain necessary similarities exist between New London and Baltimore that make these cities an ideal pairing. Both cities celebrate festivals that draw approximately 10,000 people, resulting in similar response challenges due to crowd control. Both cities are located waterside, along an extensive pier network, providing the requirement for similar maritime response.

There are advantages to simulating the event in a different setting than the original exercise. By setting the simulation in Baltimore, the results cannot be artificially "gamed" to look like the results of the exercise actually run during TOPOFF 3. In addition, transporting the scenario to different terrain shows that the methodology developed for simulation is applicable in different cities, not just in the place were the event was actually executed.

C. DESCRIPTION OF FIRST RESPONDERS

Three primary organizations provide emergency first response during a major civil crisis event: police departments, fire departments, and hospitals. The response from each organization occurs in stages, enabling these organizations to provide immediate support, not needing to wait until resources are assembled and staged. The following section is a synopsis of each organization's force structure and purpose at each phase of the crisis response operation.

The overall mission of the response forces, in priority order, is:

- Control the crowd; localizing the bomb's effect and minimizing further injuries
- Identify and eliminate additional threats

- Identify the dead
- Triage and stabilize the wounded

1. Initial Response

Initial response comes from the emergency services personnel that are in the immediate crisis area when the event occurs. The purpose of initial response is security and safety. The initial response force simulated in this exercise is comprised of police officers with two different missions. Police on foot patrol circulate throughout the Celebrate Baltimore area. Traffic police maintain positions at each intersection leading into and out of the festival area.

Foot patrols in the Inner Harbor area serve several purposes. Their primary purpose is to provide police presence and security in the area. The secondary purposes are to conduct crowd control and provide medical assistance as needed. Traffic police from several separate police departments are stationed at the intersections in the Celebrate Baltimore area. Their primary purpose is crowd control, in addition to providing police presence in the area.

There are 22 police officers who comprise the initial response police presence. Ten are on foot patrol (five patrols of two officers each) and one traffic officer stands at each of 12 intersections (see Figure 4 for a diagram of police locations). All initial response police carry similar equipment. They are armed with a standard issue 9mm semiautomatic pistol and wear Level III-A body armor, protecting them against bullet penetration from most handguns and some small caliber rifles. All police carry handheld radios capable of communicating throughout the simulation area.[20]

Following the bomb attack, both patrol and traffic police maintain their pre-attack missions. The primary focus of the police in this situation is to maintain crowd control to limit the number of casualties caused by people running away from the attack site. While maintaining crowd control, police try to identify additional threats that may attempt secondary attacks. Police on foot patrol will

[20]E-mail from Dr. Julie Seton, EPiCS Program Manager, TRAC-WSMR titled “Force Files,” dated 20 January 2006, office communication.

continue to patrol, attempting to calm as many people as possible. Traffic police will maintain their positions at intersections, keeping nonessential personnel out of the affected area in order to minimize congestion that will hamper follow-on forces.

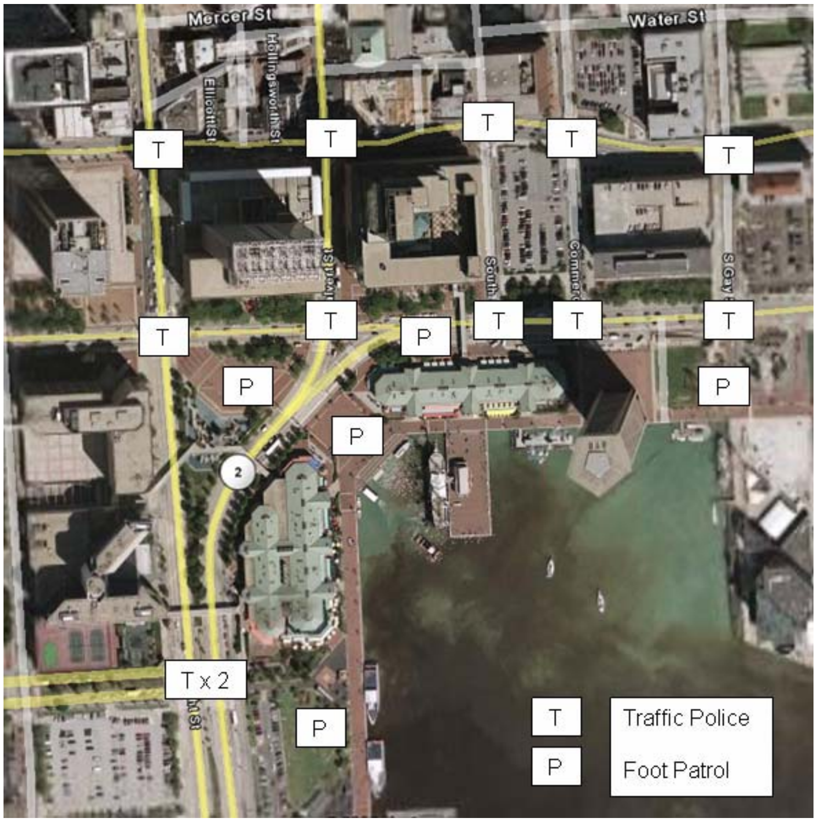

Figure 4. Array of Initial Response Forces (Police)[21]

2. Follow-On Response

Follow-on response is comprised of police, fire, and medical personnel that are summoned to the scene of the attack by the central dispatch authority. The purpose of follow-on responders is to save lives, while police continue to provide crowd control and security. The fire department controls the threat due to fire (but will also assist in the establishment of triage points), takes the lead in hazardous material situations, and provides medical assistance with its organic

[21]Graphic retrieved from Google Earth, 12 April 2004; locations are adapted from TRAC-WSMR EPiCS simulation conducted in February 2006. Free application downloaded on 30 March 2006 from the World Wide Web at http://earth.google.com/download-earth.htm.

assets. Hospitals provide doctors, nurses, and support staff to triage, stabilize, and treat injured people on-site. In addition to site support, hospitals have the ability to provide surge support at their location. Figure 5 illustrates the initial location of follow-on responders and their distance from the location of the bomb blast.

Figure 5. Follow-on Response (Police, Fire, Medical)[22]

Follow-on police response comes from the Central District Police Headquarters, approximately one-third of a mile from the scene of the explosion.[23] Police officers are diverted from their standard daily duties and phased into the response. Follow-on patrolmen have dual missions: control the

[22]Background graphics and distances courtesy of Mapquest.com. Retrieved on 30 March 2006 from the World Wide Web at http://www.mapquest.com

[23]Location of Central District Baltimore Police Headquarters. Retrieved on 30 March 2006 from the World Wide Web at http://www.ci.baltimore.md.us/neighborhoods/facilities/polfire.html

crowd to minimize the effect of panic and identify and eliminate further terrorist threats. Providing basic first aid is a tertiary task.

Follow-on police are equipped in the same manner as the initial responders. They are armed with a standard issue 9mm semiautomatic pistol and wear Level III-A body armor, protecting them against bullet penetration from most handguns and some small caliber rifles. All police carry handheld radios capable of communicating throughout the simulation area.

In addition to the diverted patrols, the district's two Special Weapons and Tactics (SWAT) teams are located at the Central District Headquarters. The SWAT teams remain on call, staged and ready at headquarters, throughout the simulation. If an armed terrorist threat is identified, the threat location is radioed to the SWAT team. The SWAT team responds, eliminates the threat, and returns to the department headquarters to await another call.

The SWAT teams have greater combat capability than the police patrols. SWAT team members carry an M4 carbine, in addition to the 9mm semiautomatic pistol. They also wear body armor that is analogous to the Army's Interceptor body armor, which is more protective than the standard Level III-A body armor worn by patrolmen. SWAT team members also carry a handheld radio that can range over the entire simulation area.

Medical responders include doctors, nurses, Emergency Medical Technicians (EMTs), and support staff from three area hospitals. Mercy Medical Center is located approximately nine-tenths of a mile north of the explosion. University Hospital is about one mile west of the scene. Saint Johns Hopkins Hospital is approximately two miles northeast.[24] Hospitals respond to the emergency with teams of ten, comprised of doctors, nurses, support staff, and associated equipment. These teams arrive incrementally, every 45 minutes, after the event. The primary purpose of the medical teams is to triage the wounded, stabilize them, and evacuate them from the scene. In addition to going

[24]Location of Baltimore hospitals. Retrieved on 30 March 2006 from the World Wide Web at http://www.local.com/results.aspx?keyword=hospital&location=Baltimore%2c+MD&radius=5

to the wounded and treating them in place, the medical teams have the responsibility of setting up triage points in the vicinity of the attack.

Fire response in this simulation comes from two nearby fire stations. Station 23 is a large, fully capable station located approximately three-quarters of a mile west of the scene of the explosion. Station 33 is a smaller station that is about three-quarters of a mile south of the explosion.[25] The primary mission of the fire department is to eliminate the threat of fire. If there is no threat of fire, the fire department will assist the police department with the evacuation of civilians from the area affected by the bomb blast. The fire department will also assist personnel from the area hospitals in setting up triage points. Stations 23 and 33 respond to the scene with similar equipment: ladder trucks, pumping trucks, and medics.

After the initial response and follow-on response by the first alarm responders, the incident commander makes a full assessment and will request second alarm responders. The mix of police, fire, and medical responders is dependent on the situation and location. This simulation does not address second alarm responders; simulating decisions made by the incident command post is beyond the scope of this research.

D. DESCRIPTION OF CIVILIANS

Ten thousand civilians are in the area of the Celebrate Baltimore festival when the terrorists detonate the bomb. There are three different classifications of civilians in the model: those unaffected by the bomb, those who are ambulatory wounded, and those that are stretcher wounded. There are four groups of the unaffected and ambulatory wounded civilians in the model: men, women, boys, and girls. Each group has separate characteristics in the model. All stretcher wounded (men, women, boys, and girls) have the same characteristics in the model.

[25] Location of Baltimore fire stations. Retrieved on 30 March 2006 from the World Wide Web at http://www.local.com/results.aspx?keyword=hospital&location=Baltimore%2c+MD&radius=5

1. Behavior of Unaffected and Ambulatory Wounded Civilians

Unaffected civilians are aware of the bomb's detonation; they want to leave the area. Civilians that are ambulatory wounded by the bomb behave in an unpredictable manner; that is, they panic. When civilians panic, they will respond to attempts by police, fire, and medical personnel to calm them. Panicking civilians will also respond to terrorist attempts to instill more panic. For example, if a civilian is moving toward a triage point because a policeman gave him directions, a terrorist can still deter the civilian and cause more panic.

2. Stretcher Wounded Civilians

Stretcher wounded civilians must be stabilized by hospital personnel (doctor, nurse, EMT) before they can move to a triage point.

E. DESCRIPTION OF TERRORISTS

Five terrorists orchestrate the simulated attack on the Celebrate Baltimore festival. Four terrorists have the purpose of increasing the level of panic experienced by the civilians in affected area. These four terrorists are in civilian clothes and attempt to blend into the crowd so as to not be readily identified by responding police officers. They do not have a weapon, but are armed with the knowledge of how to incite panic in a crowd. These terrorists focus on the areas affected by the explosion that have the largest civilian density.

The fifth terrorist is a sniper that will directly attack responding agencies to disrupt their influence on the crowd. The sniper is armed with an AK-47 assault rifle and is wearing body armor. This sniper hides in a building during the initial response and first alarm response. After the first alarm responders have arrived on scene, the sniper will begin to shoot police, fire, and medical targets of opportunity. The goal of the sniper is to slow the emergency response and incite panic in the crowd by slowly attriting response forces.

Now, with an understanding of the scenario and an overview of the forces simulated, a thorough discussion of the model follows. In addition, a detailed description of methods used to replicate behaviors and characteristics of various weapon systems is included.

III. MODELING METHODOLOGY

This chapter provides a general background of simulation and MAS, and specific details of the methodology developed to model first response to a crisis situation in a MAS environment. It begins with a brief overview of simulation models and leads to a summary of multi-agent simulations and their place in combat modeling. The author establishes the reasons for using MAS to analyze the chosen situation and the selection of Pythagoras as the particular model used. This section concludes with a detailed, step-by-step discussion of a methodology that applies MAS techniques to modeling first response in a crisis situation, and a discussion of the methodology's application.

A. SIMULATION SUPPORT TO MILITARY ANALYSIS

The Department of Defense (DoD) relies on simulation models to capture significant insights that enable senior leadership to make informed decisions. Insights gained from simulation models become especially important in areas in which experimentation is impractical or impossible. For example, it is nearly impossible to conduct actual physical experiments to determine the effectiveness of strategic or operational war plans, large-scale fielding of new force designs, or weapon system capability changes in actual conflict.[26]

> Traditional combat simulations are often complex, [high resolution] simulations that require a large amount [of] input data, an experienced and [well-trained] staff to operate and months to prepare specific scenarios for use. These issues, as well as slow runtimes, make traditional simulations both time and resource intensive. The time and resource requirements often force an analyst to conduct a very limited set of simulation runs thereby only focusing on a limited region of a [model's] input space.[27]

[26]LTC Thomas M. Cioppa, "A Potential Role of Agent Based Models in Military Analysis," Information Paper, (prepared December 2003).

[27]Ibid.

An example of why high resolution models have slow run times extends from simply capturing the effects of firing a round from a howitzer.

> To replicate a howitzer firing a projectile in a high resolution model, the analyst must know more information [than] just the classical 'trajectory in a vacuum' physics problem. Instead, the analyst must take into account interior, exterior, and terminal ballistics. Each includes, but is not limited to, factors such as projectile square weight, propellant temperature, propellant moisture, muzzle velocity variation, and tube wear effecting interior ballistics, as well as meteorological atmospheric conditions such as air temperature, air moisture, wind direction, wind speed, and the rotation of the [earth] [affecting] exterior ballistics. These examples only name a few factors that the analyst could consider when modeling the howitzer firing the projectile. This process then repeats for every other howitzer in the battery, positioned at different locations, and any other munitions also fired. As such, a simulation requiring multiple munitions, from several platforms demands significant computing ability just to provide the decision maker with useful insights required for his decision.[28]

The above is an example of the reason that simultaneous analysis of a wide range of issues is difficult with high resolution models. In addition, the traditional deterministic and even stochastic techniques that are used in these models cannot capture key elements of combat uncertainty. Factors such as synergy among actors, command and control influences, and human adaptivity—long considered strengths in the American military—are not well accounted for in traditional, high resolution models. The shortcomings of traditional models led to the search for a new tool.[29]

An innovative class of low resolution simulation, known as MAS, emerged to complement and augment previously established, more computationally intensive, physics-based, simulation models. The role of MAS is not to replace

[28]Charles A. Sulewski, "An Exploration of Unmanned Aerial Vehicles in the Army's Future Combat Systems Family of Systems," Masters Thesis, Naval Postgraduate School, Monterey, CA, December 2005.

[29]Raymond R. Hill, et al., "Some Experiments With Agent-Based Combat Models," *Military Operations Research*, Vol. 8, No. 3, 2003, pp. 17-28.

high resolution models, however, MAS increasingly proves useful to the DoD in two primary areas.

MAS may be used in **exploratory analysis**, to gain quick insight and narrow the focus of many factors, parameters, and variables to expedite using high resolution, physics-based simulations.[30] Narrowing the field of factors to explore saves time and money at the beginning of a simulation study. MAS is also used to **address key objectives** that would otherwise require extensive use of resource-intensive, physics-based models. The analyst may switch back and forth between two models to gain advanced scenario insight.[31]

Analysis of a MAS leads to a relatively fast, thorough exploration of the solution space associated with the given problem. MAS offers quick scenario generation, fast run times, rapid data turn around, and permits the analyst to consider many alternatives in a short amount of time. MAS complements and augments physics-based models, permitting analysts to examine the problem over a greater range of plausible possibilities.

MAS is an appropriate method to help an analyst provide insights that support decision makers in situations involving crisis response. Crisis response involves human decision-making, which can be unpredictable, especially under stressful situations. Decisions made by individuals can lead to global patterns or emergent behavior. MAS can help identify possible patterns and behaviors. MAS also offers the analyst the ability to run a model thousands of times to gain insight into hundreds or thousands of different "thought processes." In many circumstances, especially at the beginning of analysis, this insight is more valuable than providing a handful of point estimates that come from relatively long, expensive, high resolution runs.

[30]LTC Thomas M. Cioppa, "A Potential Role of Agent Based Models in Military Analysis," Information Paper, (prepared December 2003).

[31]Ibid.

B. PYTHGORAS BACKGROUND

The author chose Northrop Grumman's Pythagoras as the agent-based simulation modeling tool to support this research because its developers included several features in this model that are especially useful in modeling crisis response. Crisis response is inherently complex: a multisided event with many interrelationships and a requirement to gradually escalate force. Pythagoras offers a set of capabilities that is unique in the area of agent-based simulations:[32]

- Incorporates *soft rules* to distinguish unique agents
- Uses *desires* to motivate agents into moving and shooting
- Includes the concept of *affiliation* (established by *sidedness*, or color value) to differentiate agents into members of a unit, friendly agents, neutrals, or enemies
- Allows for behavior-changing events and actions (called *triggers*) that may be invoked in response to simulation activities
- Retains traditional weapons, sensors, and terrain

Northrop Grumman initially developed Pythagoras in support of Project Albert, a U.S. Marine Corps-sponsored international initiative focusing on human factors in combat and noncombat situations. They have updated the model as needed and as requested, including several updates during the development of this thesis.

The developers of Pythagoras built this model with the intent that an individual without a hard science degree could learn to effectively use the model within eight hours.[33] The company's goal of simplicity paid off. Pythagoras offers a simple-to-use Graphical User Interface (GUI), including drop-down window capabilities much like many Windows-based applications. Within a few short hours at the console, a Pythagoras novice can input a meaningful scenario and start gaining insights into the problem at hand.

[32]Henscheid, Z., *Pythagoras User's Manual*, Version 1.9, February 2006, p. 18. Retrieved from the World Wide Web on 5 February 2006 at http://www.projectalbert.org/downloads.html.

[33]Ibid.

C. METHODOLOGY OVERVIEW

The main objective of this research is to provide a methodology by which emergency first response to a crisis event can be simulated in a MAS environment. This methodology expands on areas two, three, and four of Figure 2. Figure 6 provides an illustration of the developed methodology, followed by a description of the diagram. Many of the steps are interrelated, iterative, and flexible; the given situation may require some of the steps to be accomplished in a different order than outlined in Figure 6.

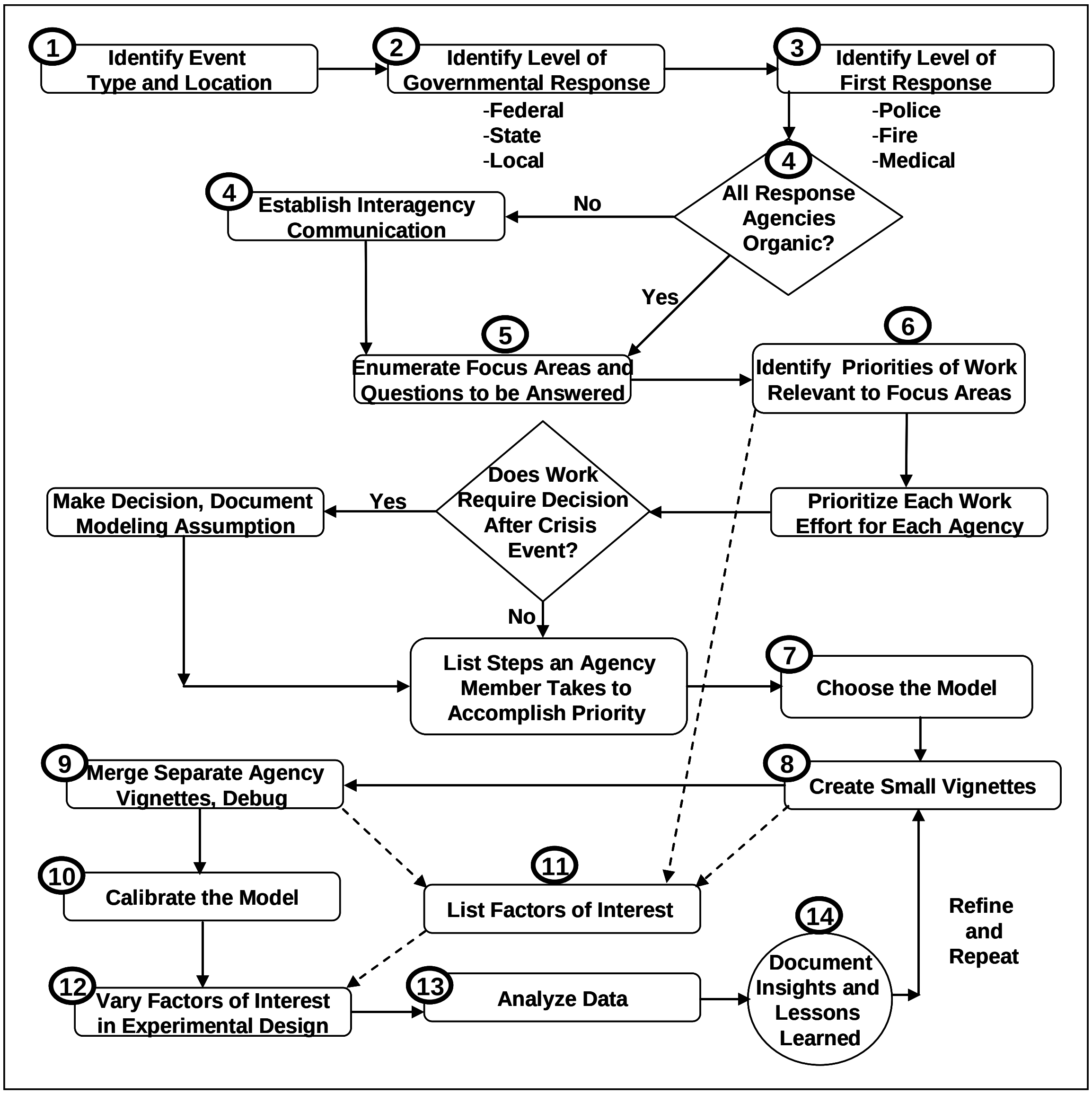

Figure 6. Methodology for Simulating Emergency First Response to a Crisis Event

The focus of this section is on steps 1 through 7 of the methodology. The author explains steps 8 and 9 in detail in Chapter IV (Model Implementation). Chapter V (Design Methodology) focuses on steps 10 and 11. Chapters VI (Data Analysis) and VII (Conclusions and Recommendations for Future Study) detail the procedures for steps 12 and 13, respectively.

The vignette modeled for this thesis is a terrorist attack in a large city (Baltimore) during a festival. This simulation is an application of the methodology, but this methodology is applicable to response in many other crises: manmade and natural, large scale and small.

1. Identify Event Type and Location

The first step in addressing a problem in a scientific manner is to define the problem. Simulating emergency first response begins with knowing the event and the location. Response to a terrorist attack is different than response to a natural disaster. Though the resources and priorities of work differ between a natural and a man-made attack, the methodology used for simulating them is the same.

2. Identify Level of Governmental Response

The analyst must consider several factors when deciding on the appropriate level of governmental response to analyze. Identifying the requirements in SOPs that govern crisis response in the appropriate situation is the first step, since procedures in different crisis events call for different levels of response. For example, federal agencies will respond to a terrorist attack without the requirement of being requested by the local government. However, in a natural disaster, the local government may need to request federal assistance.

In addition to verifying the procedurally appropriate level of response, the analyst must consider the goals of the decision maker. In a situation that would usually involve the response of the federal government, the decision makers could be city planners who are seeking to validate local plans without federal assistance.

3. Identify Level of First Response

Identifying which response agencies to include is another important step in scoping the problem. Again, the modeler must identify what the decision maker deems is important. If the simulation is meant to support a police chief's decision concerning force allocation, inclusion of other agencies may not be a requirement. In a simulation meant to support federal emergency response, it is important to simulate all facets of emergency response.

4. Establish Interagency Communication

If all agencies being simulated belong to the same organization, lines of communication for information sharing are most likely in place. Some organizations may have different parents; the next step in this simulation methodology is to establish communication between like offices in the different organizations. Information sharing is the key to a realistic, credible simulation of crisis response.

5. Enumerate Focus Areas and Questions to be Answered

With the background for the simulation set and the lines of communication open, the focus shifts to the goals the decision makers are seeking to achieve. The analyst must identify areas of interest in which the decision maker wants to gain insights. Narrowly scoped research questions will guide the direction of the simulation later in development. With the areas of interest and research questions developed, the analyst can review and prioritize agency SOPs for priorities of work needed to address the focus areas and research questions.

6. Identify Priorities of Work Relevant to Focus Areas

Identify priorities of work that occur automatically after the crisis event; also, identify priorities of work that require decisions to be made after the event occurs. The simulation can easily include decisions that are made before the event. However, MAS are simulations that are "human-out-of-the-loop." Actual human decisions stop when a constructive MAS starts. When the modeler encounters a place in the simulation where an actual human decision should be made, i.e., a decision beyond the scope of the simulation's agents, there are two ways to proceed. First, the modeler can end the simulation at the point of the human decision. Alternatively, if the decision maker needs the simulation to run longer, the modeler can make the decision before the model is run. Each decision is fully documented, complete with the reasons for making the decision.

During the process of establishing priorities of work, the analyst begins to develop the list of factors included in the model that are most important to the decision maker. During the experimental design stage of this methodology, the analyst will vary these factors to conduct the analysis that will answer the questions posed at the beginning of the project.

7. Choose the Model

When priorities of work are established and prioritized, the analyst must recognize the actions taken to accomplish those priorities. The simulation must reflect reality. The actions taken to accomplish priorities of work are important because it is these actions that determine which simulation model to use.

It may be better to use Pythagoras to simulate a model in which the decision maker is interested in leadership qualities, behavior tolerances, or affiliation changes. The decision to use Pythagoras to model the TOPOFF scenario is discussed in Section III.B. Alternatively, it may be most appropriate to use Map Aware Non-uniform Automata (MANA) if the decision maker is interested in communication architecture or situational awareness.[34] The decision maker may choose NetLogo if interested in the dynamics of crowd control or mob effects.[35]

[34]David P. Galligan, Mark A. Anderson, and Michael K. Lauren, *Map Aware Non-uniform Automata,* Version 3.0, July 2004.

[35]Uri Wilensky, *NetLogo User's Manual*, Version 3.1, April 2006. Retrieved from the World Wide Web on 19 May 2006 at http://ccl.sesp.northwestern.edu/netlogo/docs

8. Create Small Vignettes

After choosing the model, begin modeling small portions of the overall scenario. Start by modeling and debugging similar agencies or priorities, or work separately to simplify interactions among agents. See Chapter IV (Model Implementation) for detailed information on how to create vignettes in a MAS, specifically, Pythagoras.

9. Merge Separate Agency Vignettes and Debug

After debugging separate vignettes, merge the separate vignettes into one large scenario. Add and debug one vignette at a time to minimize time spent in locating errors in the model.

10. Calibrate the Model

Model calibration gains the developed simulation a measure of credibility. The model developer compares the outputs of the simulation to other, previously established outputs. For example, an analyst may compare the outputs of the model to events that actually happened, if applicable. Another way to calibrate a model is to statistically compare the model's outputs to that of another model, possibly a validated or accredited model.

11. List Factors of Interest

Developing factors of interest is an ongoing process that begins when the decision maker's priorities are established. Most relevant work on this step occurs during the time that the scenario developer is creating, debugging, and merging vignettes. After the vignettes are merged into one scenario and debugged, the factor list can be formalized, complete with the corresponding levels that provide the decision maker with desired insights. The analyst must clearly identify the desired effects of varying a given parameter. Chapter V (Design Methodology) provides detailed information on how to accomplish steps 10 and 11.

12. Varying Factors of Interest in Experimental Design

After the simulation is complete and debugged, use the power of modern computers and supercomputers to "data farm."

> Data farming is the process of using a [high-performance] computer or computing grid to run a simulation thousands or millions of times across a large parameter and value space. The result of Data Farming is a 'landscape' of output that can be analyzed for trends, anomalies, and insights in multiple parameter dimensions.[36]

13. Analyze Data

It is through the analysis of the data "grown" by the use of an efficient experimental design and data farming that insights and lessons learned are obtained and documented, and then provided to the decision maker. See Chapter VI (Data Analysis) for information about applicable data analysis techniques and results from the Baltimore Attack scenario.

14. Document Insights and Lessons Learned

Following the analysis of the model and factors, it is possible to refine the model and repeat the experiment. If the model, experimental design, and resultant data analysis meet the decision maker's needs, the analyst must document findings and lessons learned. See Chapter VII (Conclusions and Recommendations for Future Study) for documentation of the findings and recommendations resultant from analyzing the Baltimore Attack scenario.

D. METHODOLOGY APPLICATION

This section demonstrates how the previously described methodology applies to simulating the TOPOFF 3 scenario. Each step is enumerated, followed by a concise bullet comment that summarizes how the step is achieved in this research.

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[36]Definition of Data Farming. Retrieved on 9 May 2006 from the World Wide Web at http://en.wikipedia.org/wiki/Data_farming

1. **Identify Event Type and Location**

   - TOPOFF 3 scenario, large bomb VBIED, New London, CT
   - Move scenario to Baltimore with same characteristics as above

2. **Identify Level of Governmental Response**

   - Focus on city planning, do not use federal and/or state assets

3. **Identify Level of First Response**

   - Police, fire, and medical response

4. **Establish Interagency Communication**

   - Not applicable in this simulation, proof of concept exercise

5. **Enumerate Focus Areas and Questions to be Answered**

   - **Communication**: What is the most effective interagency communication architecture for emergency response to VBIED in Baltimore's Inner Harbor?
   - **Determination of Assets Required**: What is the most appropriate mix of police, fire, and medical assets?

6. **Identify Priorities of Work Relevant to Focus Areas**

   - Identify/neutralize additional threats
   - Coordinate initial and follow-on response
   - Identify dead and wounded
   - Stabilize wounded, move to triage site
   - Restore calm

7. **Choose the Model**

   - Use Pythagoras

8. **Create Small Vignettes**

   - Terrorist agitators incite panic in crowd

- Police on patrol, looking for wounded, threats
- Arrival of medics, treatment of stretcher wounded
- Incident command post, fusion of communication across different agencies
- Integration of SWAT team, response to threat
- Arrival and deployment of fire department
- Arrival and deployment of police follow-on response
- Terrorist gunman hides and attacks targets of opportunity

9. Merge Separate Agency Vignettes and Debug

- The small vignettes are merged into one overall simulation, see Chapter IV (Model Implementation)

10. Calibrate the Model

- A rigorous way to calibrate this simulation model is to generate a distribution of outputs, then compare the results to one EPiCS run, or a distribution of outputs gained from several EPiCS runs. The capability does not currently exist to run several EPiCS simulations and capture the needed data.
- The author calibrated this model through the use of modeling subject matter expertise at the Naval Postgraduate School and his own personal expertise in the area of emergency first response operations. This calibration was conducted using a qualitative comparison of the outputs this simulation and EPiCS can provide.

11. List Factors of Interest

- See Chapter V (Design Methodology)

12. Varying Factors of Interest in Experimental Design

- See Chapter V (Design Methodology)

13. Analyze Data

- See Chapter VI (Data Analysis)

14. Document Insights and Lessons Learned

- See Chapter VII (Conclusions and Recommendations for Future Study)

This section has provided the reader with a general overview of simulations and specific information about the MAS, Pythagoras. The author establishes and explains a methodology by which an analyst can use MAS to model emergency first response to a crisis event. The section concludes with an overview of how Pythagoras can be used in the application of the methodology to model a TOPOFF scenario. In subsequent sections, the “nuts and bolts” of the model are explained, including settings, assumptions, and limitations. In addition, the process of experimental design in this simulation is discussed, with the resultant data analysis and conclusions.

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IV. MODEL IMPLEMENTATION

This chapter provides a detailed, step-by-step discussion of the techniques used to model emergency response to a crisis in a MAS. The modeling described here corresponds to steps 8 and 9 of the methodology outlined in Figure 6 and subsequently discussed. Additionally, this chapter will touch on step 10, calibration of the model. The following includes details that address Pythagoras's model settings specifically, but can be generalized to be applicable to other models. The chapter concludes with a discussion of known "bugs" in the model and the model's limitations.

A. MODELING TECHNIQUE

This section contains general information that can be used to create the scenario within most any MAS. In addition, this section contains detailed information that describes how this simulation was created in Pythagoras. Appendix A (Model Implementation) contains Excel tables and Pythagoras screen shots that illustrate ideas discussed here in writing. The first section of Appendix A outlines the creation of the environment in which the simulation occurs. It is the translation of the actual world into the simulation world. In the subsequent sections, the author describes the different types of agents in the scenario and the interactions among agents in each major event. The detailed discussion includes the goals of each organization involved, modeling techniques used to capture the effects of organizational operations, and the assumptions made.

The author does not claim that the tactics modeled in this simulation are optimal emergency response tactics, techniques, and procedures (TTPs). This simulation does provide a proof of concept that it is possible to model emergency response priorities and TTPs in a multi-agent environment. The power of this tool is that it is possible to quickly adapt this model and this scenario to analyze many different force structures, TTPs, organizational priorities, and even other crisis events.

1. Overall Model Configuration

a. Scaling the Model

The first step of using a simulation model is scaling the model's workspace to represent the area of interest. Traditional units of measure include feet, miles, meters, or kilometers. This scenario includes a "terrain box" that is four million square feet of the Baltimore Inner Harbor, 2,000 feet long by 2,000 feet wide (see Figure 7). The unit of measure in Pythagoras is the pixel; the size of the model's terrain is 1,000 pixels by 1,000 pixels. In this vignette, one pixel represents two feet. Appendix A includes a detailed discussion about the scaling of this simulation, including the measurement of distances.

Figure 7. Comparison of Actual Terrain[37] in Baltimore's Inner Harbor to Terrain in Model

[37]Graphic retrieved from Google Earth, 12 April 2004; locations are adapted from TRAC-WSMR EPiCS simulation conducted in February 2006. Free application downloaded on 30 March 2006 from the World Wide Web at http://earth.google.com/download-earth.htm.

b. Timestep

Time in Pythagoras is measured by timesteps. It is important to give careful consideration to the determination of the translation from seconds to timesteps. Agents move from their previous position to their subsequent position by jumping directly to the desired position. Agents do not pass through the pixels between positions. A timestep that represents a long period of real-time could result in agents “jumping” past each other and not interacting. A timestep that represents too little real time could result in the simulation requiring a vast amount of CPU time to run. For this vignette, the author chose one timestep to represent four seconds, resulting in a simulation of one hour of time that runs for 900 timesteps.

c. Terrain

Terrain is defined by its characteristics. A given terrain feature will have a certain height; it may offer visibility through it, restrict movement, and have a protective value. Different types of terrain, as seen in Figure 6, have different colors, which are chosen by the user, not the developers. Gray terrain in one simulation may be easily trafficable concrete; in another simulation, gray could be an impenetrable wall. In Pythagoras, concealment occurs in three “bands”—A, B, and C. These bands are associated with the possible selections for available sensors in the model. More discussion about sensing bands follows in Section IV.A.1.f. See Table 1 for Pythagoras terms associated with its terrain. Specific characteristics for all weapons included in this simulation are located in Appendix A, Section A.1.c.

Subject	Actual Terminology	Pythagoras Language	Scale
Height	Height (feet)	Height (pixels)	0 – 1,000
Sight	Visibility	Concealment	0.0 – 1.0
Movement	Trafficability	Movement Factor	0.0 – 1.0
Protection	Cover	Protection	0.0 – 1.0

Table 1. Translation of Pythagoras Terrain Terms

Concealment, movement factor, and protection are multipliers that affect the probability of detection, rate of movement, and probability of being killed. For example, a wall made of cinder blocks may have a height of 20 feet (10 pixels). A person cannot see through the wall, so the concealment factor is 1.0. The probability of detection results from the following formula:

$$\text{Actual } P_D = [1 - (\text{Concealment Factor})] * \text{Baseline } P_D$$

A person cannot walk through a wall that is 20 feet tall, thus the movement factor would be 0.0; therefore, the movement rate is 0: 0.0 * standard movement rate.

Suppose the weapons included in the simulation cannot shoot through a cinder block wall. The protection value would be 1.0. The probability of kill for a weapon trying to shoot through the wall is 0, because Pythagoras includes (1-protection factor) as a multiplier in determining actual probability of kill for a given situation. The author addresses movement rates in greater detail in Section IV.A.3.a. See Table 2 for the types of terrain included in this simulation.

Color	Name	Height	Concealment	Movement Factor	Protection
Gray	Concrete	0.0	0.0	1.0	0.0
Black	Road	0.0	0.0	1.0	0.0
Light Green	Water	0.0	0.0	0.0	0.0
Purple	Building	28	1.0	0.0	1.0
Dark Purple	Tall Bldg	60	1.0	0.0	1.0
Tan	Inside Bldg	0.0	0.0	1.0	0.0
Light Purple	Rubbling	3 pixels	0.5	0.2	0.0
Red	Triage Site	0.0	0.0	1.0	0.0

Table 2. Terrain Colors Used in Baltimore Attack

d. Weapons

One way that an agent interacts with other agents is through the use of "weapons." Weapons in most simulation models, and Pythagoras in particular, are not limited to killing enemies. Table 3 describes the different types of influence that Pythagoras weapons can impart. In general, weapons influence the target's health, sidedness, or another user-selected attribute. Changes in sidedness and attributes are discussed in detail later in this section.

Weapon Class	Weapon Effect	Example Usage
Killing	Decrease Target's Health	Policeman's Pistol
Restorative	Increase Target's Health	EMT's Medical Kit
Paintball	Incremental Side or Attribute Change	Propaganda Leaflets

Table 3. Pythagoras's Weapon Effects

Table 4 provides a breakdown of the different weapons used in this simulation; who uses them and their effects. Appendix A includes detailed weapon information. The United States Army Materiel Systems Analysis Activity (AMSAA) provided weapon characteristics for the M4 rifle, M9 pistol, and AK-47 assault rifle. Characteristics of other weapons are the result of the author's experience as a military policeman, in addition to informal conversations with police, Special Forces operators, and other subject matter experts. More detailed information about agent side properties is included in Appendix A, Section A.1.d.

Weapon	WPN Class	Weapon Carrier	Target	Effect
9mm	K*	Police	Enemies	Decrease Health
AK-47	K	Terrorist Gunman	Enemies	Decrease Health
Agitator	P**	Covert Terrorist	Enemies	Cause Panic
Bomb	K	None	All	Decrease Health, Cause Panic
Rock	K, P	Panicking Civilians	All	Decrease Health, Cause Panic
M4	K	SWAT	Enemies	Decrease Health
Medical Kit	R***	EMT	Friends	Increase Health
Orders	P	Police, EMTs, Firemen	Friends	Calm Panic, Send to Med Station

*K denotes "killing" weapon, lethal effects
**P denotes "paintball" weapon, nonlethal effects
***R denotes "restorative" weapon, healing effects

Table 4. Weapons Modeled in Baltimore Scenario

The effect that a given weapon has on its target is calculated by multiplying the following factors:

- Probability of hit associated with the weapon, as a function of range
- Shooting agent's marksmanship
- Probability of kill of the weapon (given a hit)

- The effectiveness of the weapon (lethality)
- Vulnerability of the agent being shot
- Protection factor offered by the terrain

e. Agent Side Property

Side property is a feature that is unique to the Pythagoras model, allowing the inclusion of many different sides in a simulation, not just friends and enemies. The modeler assigns sides to the agents using color combinations of blue, green, and red. Each color is established on an integer scale between 0 and 255. The modeler then establishes a color radius to determine unit membership, friendship, neutrality, and who is an enemy. Agents will assess each other's color and compare it to their own color to determine affiliation, based on the distance between the two agents' colors and the unit, friend, and enemy color radii.

Table 5 shows a simple example of friend, neutral, and enemy affiliation, using only the color blue.

Agent 1	Unit Radius	Friend Radius	Enemy Radius	Agent 2	Result
255, 0, 0	10	20	50	255, 0, 0	Unit Member
255, 0, 0	10	20	50	240, 0, 0	Friend
255, 0, 0	10	20	50	210, 0, 0	Neutral
255, 0, 0	10	20	50	150, 0, 0	Enemy

Table 5. Determination of Affiliation by Color

Pythagoras enables the modeler to use any combination of blue, green, and red to determine affiliation. In using combinations of two or more colors to determine affiliation, the modeler must decide on one of two methods to calculate distance between the agents' colors.

Manhattan Distance (used in this thesis) is the result of adding the color differences in each of the three colors, and is calculated by using the following formula.

$$d = \left|\text{Blue}_2 - \text{Blue}_1\right| + \left|\text{Green}_2 - \text{Green}_1\right| + \left|\text{Red}_2 - \text{Red}_1\right|$$

The mathematical, or straight line, distance between the two colors, also called the Euclidean Distance, is calculated using the following formula.

$$d = \sqrt{(\text{Blue}_2 - \text{Blue}_1)^2 + (\text{Green}_2 - \text{Green}_1)^2 + (\text{Red}_2 - \text{Red}_1)^2}$$

There are many sides represented in this simulation. There are the public servants (police, fire, and medical personnel), the public (civilians), and the danger to the public (terrorists). Police are separated into several different sides, representing police from different districts. The terrorists are also divided into two sides: those that incite panic and those that attack the first responders. Table 6 highlights the different sides and their relationship to each other.

	Unit	Friend	Enemy
1. Inner Harbor Police	1	1-6	7-8
2. Traffic Police	2	1-6	7-8
3. SWAT	3	1-6	7-8
4. Central District Police	4	1-6	7-8
5. Fire Departments	5	1-6	7-8
6. Hospital	6	1-6	7-8
7. Terrorist Agitators	7, 8	7, 8	1-6
8. Terrorist Gunman	7, 8	7, 8	1-6

Table 6. Relationship Between Sides

f. Sensors

In Pythagoras, a sensor's ability to detect an agent is based on three factors: the detection ability of the sensor, the terrain's concealment factor, and the agent's detectability. Each of these factors occurs over three bands: A, B, and C. These three bands enable the modeler to simulate three different types of detection, e.g., visual spectrum, thermal detection, and infrared. A piece of terrain may deny the agent an ability to see with the naked eye, but visibility is possible with an infrared or thermal device.

In this simulation, agents have one sensor, eyes, which detect in the visual spectrum. All agents are completely detectable. The limiting factor is the concealment factor of the terrain, previously outlined in Table 2. Figure 8 shows the effectiveness of eyes by range, across terrain with no concealment factor. To find the actual probability of detection, use the following formula:

$$\text{Actual } P_D = [1 - (\text{Concealment Factor})] * \text{Baseline } P_D$$

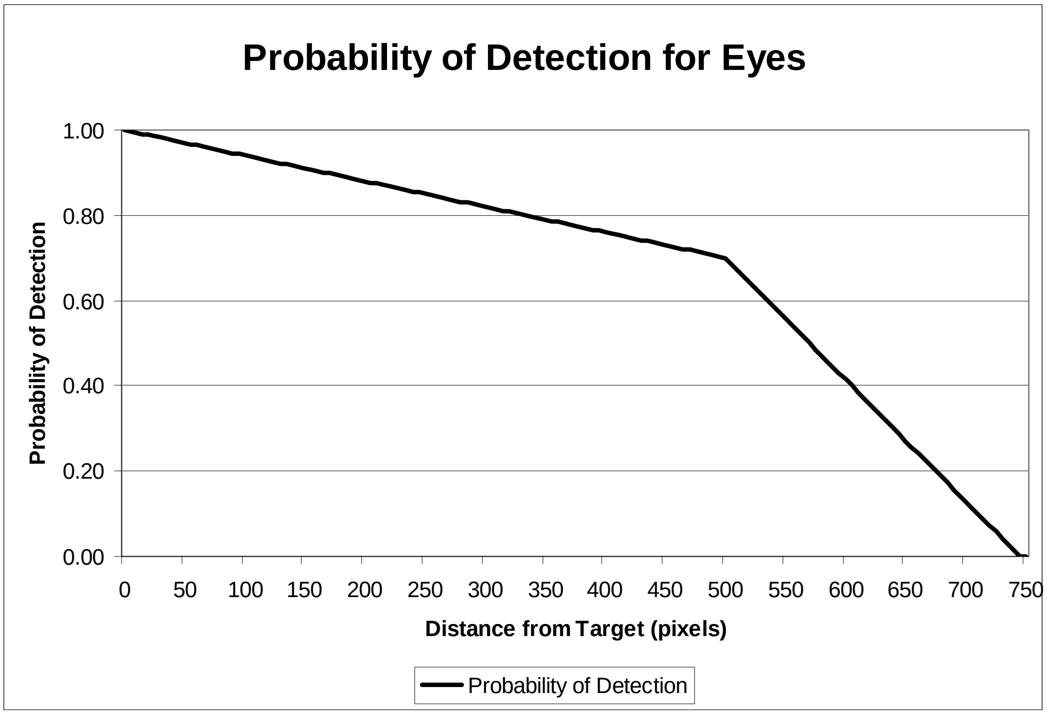


Figure 8. Baseline Probability of Detecting a Target Using Eyes

g. Communication Devices

Communication devices are available for agents to pass information to each other. In general, there are two major types of communication devices: those that require line of sight and those that have broadcast capability and therefore do not require line of sight. Pythagoras enables modelers to vary the probability of successful communication with a given device. By changing the probability of successful communication, the analyst can make an assessment concerning the importance of a solid communication network in a given situation.

In this simulation, each agent is given a voice and a line of sight communication device. See Figure 9 for the probability of successful communication for an agent using its voice. Each police, fire, and medical unit has a broadcasting communication device that simulates the handheld radio commonly carried by each agency in their daily duties. The handheld communication device is capable of communicating over the entire simulation area.

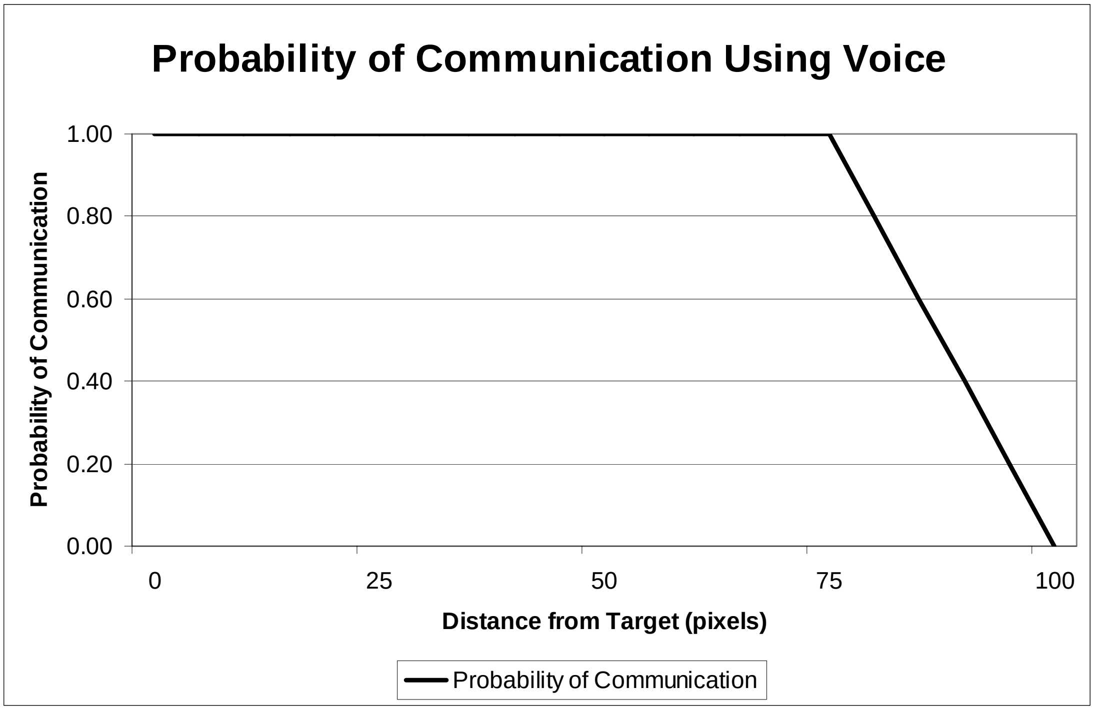


Figure 9. Probability of Successful Communications Using Voice

h. Agent "Personalities"

A definition for personality is "the total of qualities and traits, as of character and behavior, that are peculiar to a specific person."[38]

Agent personalities in this MAS result from the effects of their behaviors on the surrounding environment, including other agents. Specifically, the types of behaviors that are used to define agent personalities are: the desire to hold fire in the presence of enemies (aggression), leadership and obedience, movement desires, and alternate behaviors that are triggered by a certain action or condition.

(1) Hold Fire Desire. In Pythagoras, the modeler controls an agent's hold fire desire by assigning the agent a number on a scale of 0 to 1. A

[38]Definition of Personality. Retrieved on 10 May 2006 from the World Wide Web at http://www.dictionary.com

hold fire desire of 1 is analogous to restrictive rules of engagement (ROE), in which the agent will not fire unless fired on. A hold fire desire of 0.5 means that half the time when an agent sees an enemy, that agent will fire first, and half the time that agent will not fire unless fired on. A hold fire desire of 0 is analogous to a "free-fire zone" in which the agent will shoot as soon as an enemy is identified. When the decision to engage has been made, the agent must decide from one of possibly three weapons. The modeler must identify if the agent will select the weapon with the highest probability of kill, the lowest, or the medium P_k.

(2) Leadership and Obedience. Pythagoras enables the creator of the simulation to incorporate leadership and obedience into the agents' personality profiles. There are two different types of leaders in Pythagoras: charismatic and hierarchical. When exposed to charismatic leadership, the agents within the unit will respond to the leader with the highest leadership value, a value between 0 and 100. In hierarchical leadership, the agent will follow the leader that has the smallest leadership value higher that its own leadership value. Agents follow their leadership in accordance with their obedience value, established by the simulation's creator on a scale of 0 to 1. An agent with an obedience value of 0.5 will only follow orders half of the time.

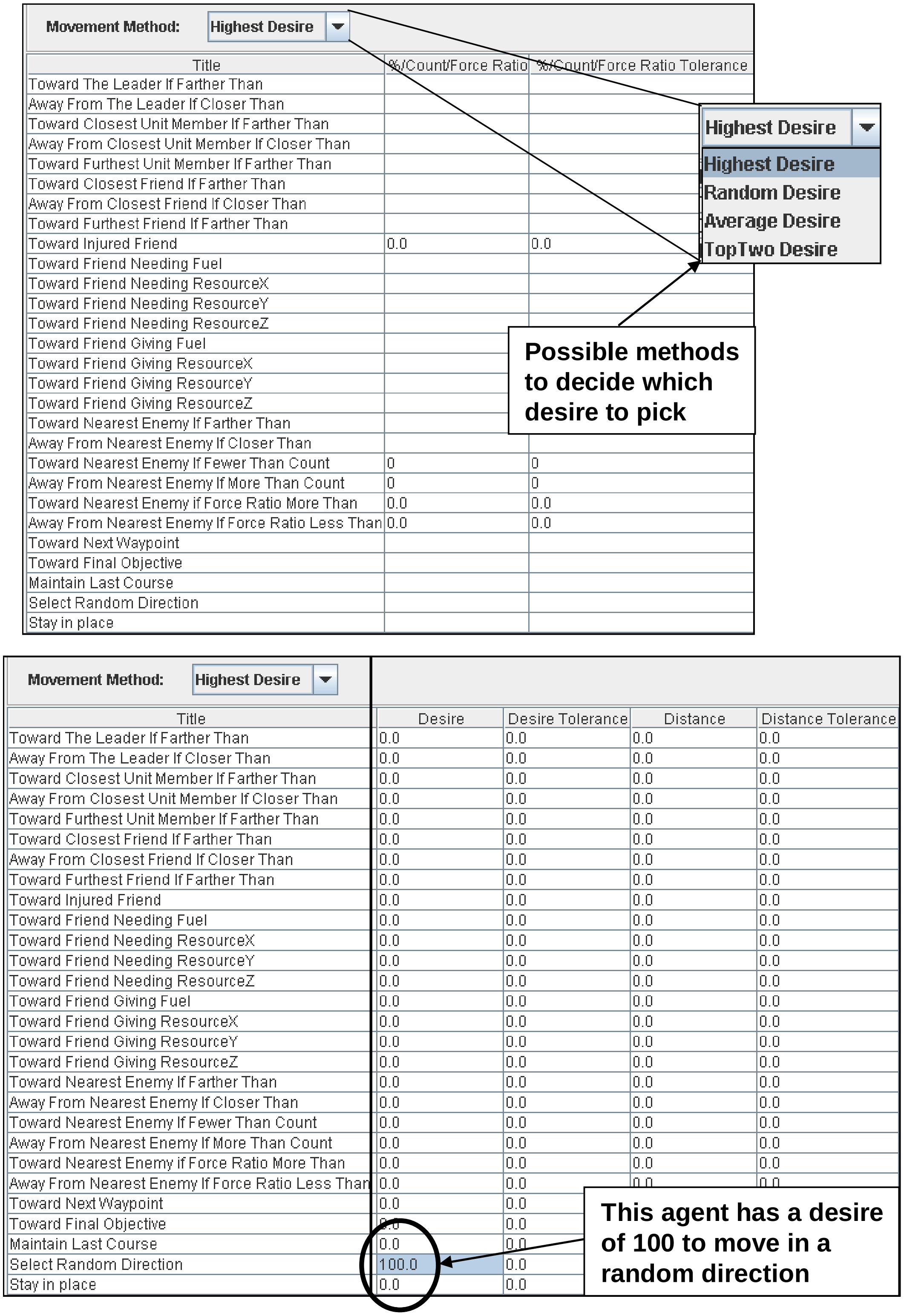
Leadership and obedience each have a "tolerance" associated with them. This tolerance provides a way for the modeler to capture the effect of people interpreting situations differently. The tolerance is on the same scale as the initial trait. A small tolerance would indicate a predictable, disciplined outcome. A large tolerance indicates more randomness, with possibly less discipline and less predictability.

(3) Movement Desires and Alternate Behaviors. The developers of Pythagoras provide the modeler with several distinct movement desires that help to shape each agent's simulated personality. Figure 9 provides a depiction of available movement desires. Each movement has a corresponding desire and desire tolerance. The modeler decides which desires to activate within each agent. These desires are adjusted by the modeler until the agents move as desired. Every desire is assigned a number between

0 and 100. An agent with a high movement desire is more likely to execute that behavior. Event movement desire has a tolerance associated with it, similar to leadership and obedience.

In addition to the desire fields, there are movement desires that correspond to a desire to move away from or toward other agents. These desires are based on counts or ratios. For example, an agent may have the desire to move away from an enemy if the force ratio is greater than a certain number. Similar desires correspond to distances. An agent may have the desire to move toward the nearest unit member if that unit member is farther away than a certain threshold. The movement desire tab enables the modeler to explicitly define these thresholds. As with the desired tolerance, the modeler can implicitly capture a measure of discipline or organization by using the tolerances associated with ratios or distances.

The agent "decides" which desire to select by virtue of a choice the modeler makes, illustrated in Figures 10 and 11. The agent can move in accordance with its highest desire. It can also select a desire randomly, based on the draw of a random number. In addition, the decision may be made by calculating a weighted, vector average of the active desires. Finally, the modeler may decide to enable the agent to move in accordance with a weighted average of its top two desires.



Title	%/Count/Force Ratio	%/Count/Force Ratio Tolerance
Toward The Leader If Farther Than		
Away From The Leader If Closer Than		
Toward Closest Unit Member If Farther Than		
Away From Closest Unit Member If Closer Than		
Toward Furthest Unit Member If Farther Than		
Toward Closest Friend If Farther Than		
Away From Closest Friend If Closer Than		
Toward Furthest Friend If Farther Than		
Toward Injured Friend	0.0	0.0
Toward Friend Needing Fuel		
Toward Friend Needing ResourceX		
Toward Friend Needing ResourceY		
Toward Friend Needing ResourceZ		
Toward Friend Giving Fuel		
Toward Friend Giving ResourceX		
Toward Friend Giving ResourceY		
Toward Friend Giving ResourceZ		
Toward Nearest Enemy If Farther Than		
Away From Nearest Enemy If Closer Than		
Toward Nearest Enemy If Fewer Than Count	0	0
Away From Nearest Enemy If More Than Count	0	0
Toward Nearest Enemy if Force Ratio More Than	0.0	0.0
Away From Nearest Enemy If Force Ratio Less Than	0.0	0.0
Toward Next Waypoint		
Toward Final Objective		
Maintain Last Course		
Select Random Direction		
Stay in place		

Title	Desire	Desire Tolerance	Distance	Distance Tolerance
Toward The Leader If Farther Than	0.0	0.0	0.0	0.0
Away From The Leader If Closer Than	0.0	0.0	0.0	0.0
Toward Closest Unit Member If Farther Than	0.0	0.0	0.0	0.0
Away From Closest Unit Member If Closer Than	0.0	0.0	0.0	0.0
Toward Furthest Unit Member If Farther Than	0.0	0.0	0.0	0.0
Toward Closest Friend If Farther Than	0.0	0.0	0.0	0.0
Away From Closest Friend If Closer Than	0.0	0.0	0.0	0.0
Toward Furthest Friend If Farther Than	0.0	0.0	0.0	0.0
Toward Injured Friend	0.0	0.0	0.0	0.0
Toward Friend Needing Fuel	0.0	0.0	0.0	0.0
Toward Friend Needing ResourceX	0.0	0.0	0.0	0.0
Toward Friend Needing ResourceY	0.0	0.0	0.0	0.0
Toward Friend Needing ResourceZ	0.0	0.0	0.0	0.0
Toward Friend Giving Fuel	0.0	0.0	0.0	0.0
Toward Friend Giving ResourceX	0.0	0.0	0.0	0.0
Toward Friend Giving ResourceY	0.0	0.0	0.0	0.0
Toward Friend Giving ResourceZ	0.0	0.0	0.0	0.0
Toward Nearest Enemy If Farther Than	0.0	0.0	0.0	0.0
Away From Nearest Enemy If Closer Than	0.0	0.0	0.0	0.0
Toward Nearest Enemy If Fewer Than Count	0.0	0.0	0.0	0.0
Away From Nearest Enemy If More Than Count	0.0	0.0	0.0	0.0
Toward Nearest Enemy if Force Ratio More Than	0.0	0.0	0.0	0.0
Away From Nearest Enemy If Force Ratio Less Than	0.0	0.0	0.0	0.0
Toward Next Waypoint	0.0	0.0		
Toward Final Objective	0.0	0.0		
Maintain Last Course	0.0	0.0		
Select Random Direction	100.0	0.0		
Stay in place	0.0	0.0		

Figure 10. Pythagoras Movement Desires

Behaviors define agents' personalities in a MAS. As the simulation progresses, the agents respond to stimuli in their environment in different ways. These alternate behaviors define the agents' personalities as much as the behaviors activated at the beginning of the simulation. The author of the simulation creates alternate behaviors to capture an effect that occurs within the simulation. For example, at timestep one, when the bomb explodes in this simulation, it triggers the civilians to panic. The specific trigger is the timestep; at timestep one, the properties of the civilians change to reflect feeling the effects of the bomb, then panicking. There are several event triggers provided in Pythagoras, some examples of which are illustrated in Table 7.

Trigger	Trigger Event Value	Alternate Behavior Triggered	Alternate Behavior Ordered
Absolute Timestep	60	EMTs travel to site	N/A
Know About Enemy	1	N/A	Kill Enemy
Arrive at Objective	N/A	EMTs evac wounded	N/A
Relative Timestep	450	Fire Dept. leaves rubble	N/A

N/A = Not Applicable.

Table 7. Example Alternate Behavior Triggers

The author defined the panic behavior by changing certain qualities of the agents affected, including rate of movement, movement desires, and a establishing a need to be "calmed." See Table 8 for a list of alternate behaviors developed for this thesis. Behaviors of each individual class of agent in the simulation will be discussed later in this chapter, in each respective section, one for each class.

Alternate Behavior Name	Agent Class Affected	Behavior Description
Feel Effects of Bomb	All civilians	Precursor to panic
Panic	All civilians	Increase speed, need calm, avoid enemy
Wait for Medic	Stretcher civ	Stay in place until medic comes
Go to Medical Station	All civilians	Move to established triage point
Move to Rubbling Area	Fire Depts	Deploy from home fire stations
Evacuate from Rubble	Fire Depts	Provide aid to civilians in rubble
Travel from Hospital	EMTs	Move from Mercy Medical and St. Johns
Evac Stretcher Wounded	EMTs	Provide aid, bring SW civs to triage point
Attack Responders	Gunman	Attack civilians and first responders
Begin Incident Command	Unit Leaders	Incident command post operational
Kill Enemy	SWAT	Command post dispatches SWAT
Building Clearing	Police	Follow-on police clear affected buildings

Table 8. List of Alternate Behaviors

Now that the overall setting for the simulation model is established, the following section will provide information about the representation of the individual agents defined in the simulation. The section is arranged by agent type, describing the following agents in detail:

- The bomb detonated in the amphitheater
- Civilians: Stretcher wounded and those that are “walking wounded” or physically unaffected by the bomb
- Terrorists: Covert agents that incite panic, gunmen that aggress responders
- Police: Traffic police, patrolmen, follow-on responders, incident commanders, and the SWAT team
- Firemen from two departments
- Medical personnel from two different hospitals

For all agents except the bomb, the author will describe the agent class’s activities in plain language, including a diagram that highlights transition points between behavior states when necessary (see Appendix A for more detail). A description of the Pythagoras modeling of the agent class’s behavior follows the plain language discussion.

2. The Bomb

The bomb that explodes during the Celebrate Baltimore festival is a device approximately the same size as the bomb that destroyed the Murrah Federal Office building in Oklahoma City in 1995. It is the equivalent of approximately 7,350 pounds of ammonium nitrate, in twenty-two 55-gallon drums.[39] The size of the bomb is assumed before the simulation begins and does not change. This assumption is required because the terrain in Pythagoras is static. When the simulation begins, the terrain is fixed; there is no mechanism by which the modeler can enable the strength of the bomb blast to automatically alter the terrain. If the modeler sought to analyze different bomb strengths, different areas of rubbling must be built.

a. Cookie Cutter Damage Function

Damage inflicted on people within the rubbling area is assessed using a cookie cutter damage function. There is no partial damage assessment resultant from the cookie cutter damage function; an agent within the effective radius is killed or not killed, based on the probability of kill associated with that weapon. The author chose to use the cookie cutter damage function for modeling the close-in damage caused by the bomb to capture the effect of a person possibly being shielded by a support beam or other covering object, and not being hurt by the blast. It is possible that an agent survives the cookie cutter blast effect, but is damaged by the Carleton damage effect outlined below. Note: The two blast radii overlap. See Figure 11 for the blast radii associated with the cookie cutter and Carleton damage functions.

[39] E-mail from Dr. Julie Seton, EPiCS Program Manager, TRAC-WSMR, titled “Message from Dan Edmonson – CT Incident Details for TRAC-Monterey Project,” 24 January 2006, office communication.

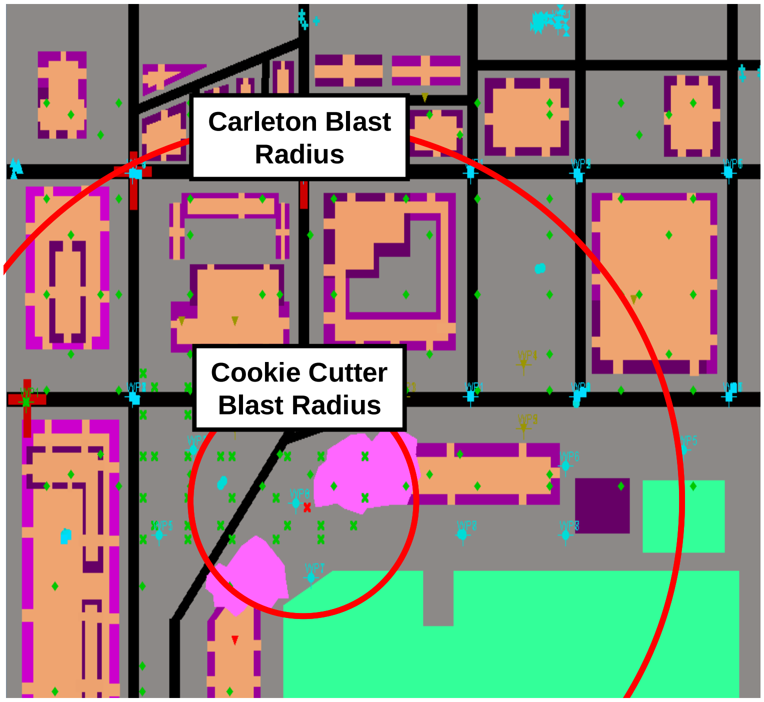
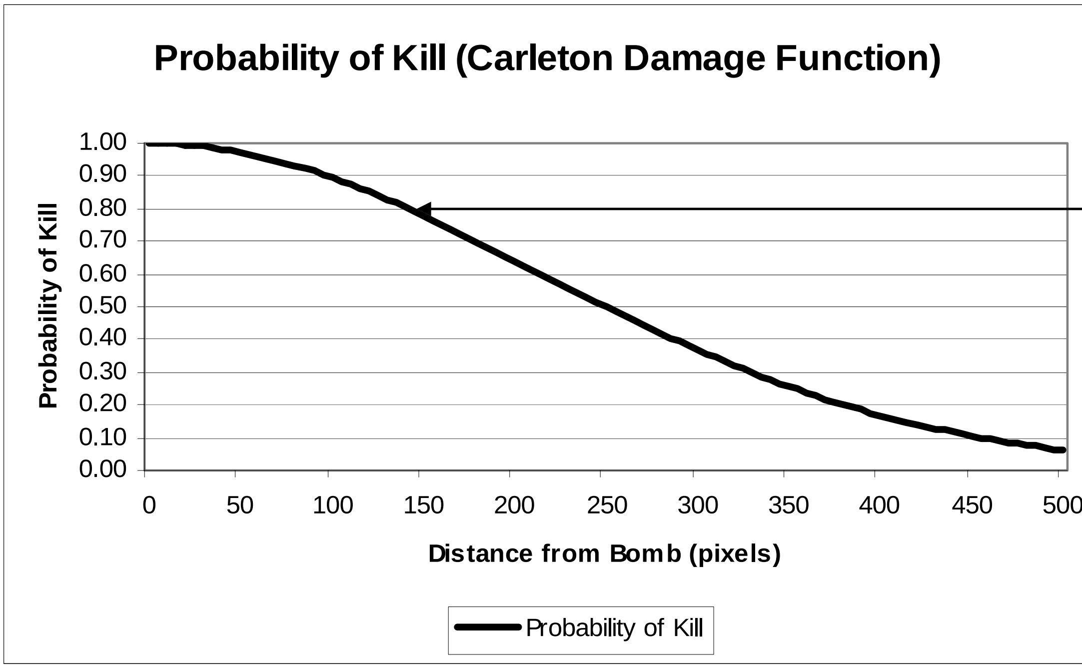


Figure 11. Illustration of Blast Radii

b. Carleton Damage Function

Damage caused to people outside the rubbling range is assessed using the Carleton damage function, a well-documented method for calculating damage done by an indirect fire weapon. The author chose the Carleton damage function to capture the effect of decreased damage to the people that are far away from the blast. Figure 12 illustrates the relationship between probability of kill (P_k) and distance with the Carleton damage function.



$$P_k = e^{-[(\text{distance from blast})^2 / (\text{bomb damage radius})^2]}$$

Figure 12. Probability of Kill Using the Carleton Damage Function

A large explosion will cause psychological effects, in addition to the physical effects felt by people within the blast radius. The psychological effects are not limited to people directly (physically) affected by the bomb; panic in a large-scale crisis event can be pervasive throughout the area. The technique for modeling panic in the civilian population follows in the next section.

3. Civilians

In a crisis situation, the civilians involved can be regarded as two separate classes: those that can move by themselves (physically unharmed or “walking wounded”) and those that cannot (“stretcher wounded”). In this simulation, the two are modeled differently. Within the two classes of civilians, men, women, boys, and girls are modeled with different characteristics.

a. Ambulatory Wounded and Uninjured Civilians

At the beginning of the simulation, all civilians wander randomly through the Celebrate Baltimore area in Baltimore's Inner Harbor. After the explosion of the bomb, civilians that are ambulatory wounded or physically unharmed follow the events depicted in Figure 13.

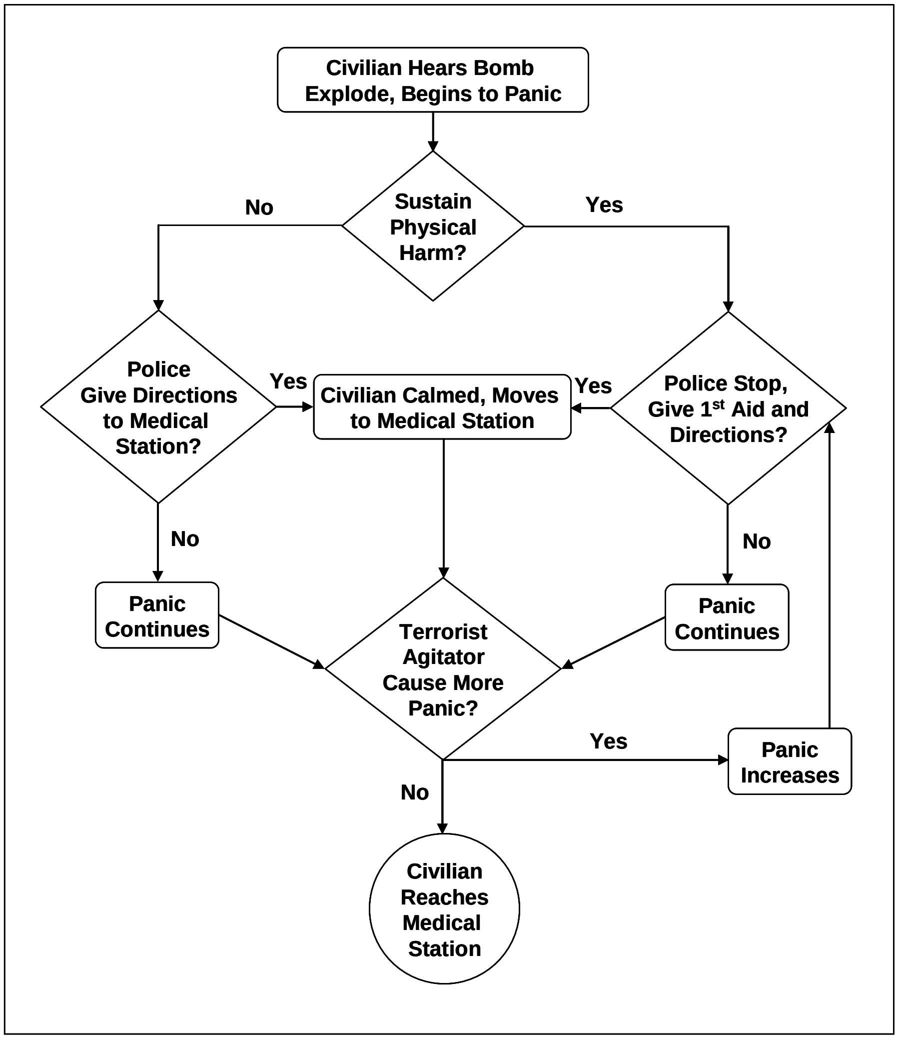


Figure 13. Flow Chart of Uninjured and Ambulatory Wounded Civilian Activity

At timestep one, the bomb explodes in the Baltimore Inner Harbor Amphitheater. All of the civilians in the area panic, including those that are uninjured, slightly injured, and seriously wounded. If a person is slightly injured, one of the emergency first responders must stop, render first aid, and provide directions to the medical triage point that is being set up. Through the interaction between first responder and civilian, the civilian is calmed down and begins to move to the triage point. If the civilian is uninjured in the bomb blast, their feeling of panic is less than someone who was injured. To assuage their feeling of panic, a first responder merely needs to spend 30 seconds calming them down and providing directions to a triage point at one of three locations outside the area affected by the blast.

Civilians will continue to panic until a first responder provides them with the level of comfort that they need. As civilians move to the triage point, it is possible that a terrorist agitator encounters them and causes them to panic again. If this happens, a first responder must identify the newly panicking civilians and calm them again. If a civilian has not been calmed by a first responder and a crowd agitator finds them first, it will take the first responder longer to calm the civilian and put that person on the path to the triage point.

(1) Common Qualities. All civilian agents have eyes that are instantiated as sensors and voice as a communications device, as previously stated. Civilians do not carry weapons.

(2) Movement Rates. See Table 9 for a translation of Pythagoras-specific terms into values that are more familiar to us. The movement rates and the sensing information are data derived from AMSAA. When calm, civilians move at an average speed of 4 kilometers per hour (kph), or at about the pace of an average walk. The maximum speed that a civilian can move while calm is 16 kph, or approximately running speed. When panicked, civilians have an average speed of 11 kph, with a maximum speed of 22 kph, which is a sprint. Appendix A, Section A.1.e. includes a snapshot of the spreadsheet used to develop movement rates throughout this research.

Characteristic	Value (Pythagoras)	Tolerance (Pythagoras)	Value (Actual)	Tolerance (Actual)
Movement Rate (Calm)*	7	22	4 kph	12 kph
Movement Rate (Panic)*	20	20	11 kph	11 kph
Sense and Detect*	Eyes			
Communication	Voice			
Weapons	None			
Vulnerability (Man)	0.5	0		
Vulnerability (Woman)	0.75	0		
Vulnerability (Boy and Girl)	1.0	0		

*Derived from AMSAA data.

Table 9. Uninjured and Ambulatory Wounded Civilian Characteristics

(3) Civilian Vulnerability. Vulnerability corresponds to the amount of protection an agent has from its environment, e.g., a police officer's body armor. In this simulation, men, women, and children have different vulnerability levels. The specific assignment of vulnerability levels is not scientific. It is a demonstration that it is possible to assign characteristics to civilians that can highlight differences between men, women, and children in this situation. For this simulation, men have half the vulnerability value of children. Women are halfway between men and children.

(4) Alternate Behaviors. Civilians of this class have two alternate behaviors: feeling the psychological effects of the bomb and panic.

(a) Feeling Psychological Effects of the Bomb. When the bomb explodes, civilians hear the bomb and they become afraid. With the fear they feel, the civilians also gain a need to be calmed. In simulation, the author modeled fear with Pythagoras's "attribute alpha." When the bomb explodes, every civilian is given 10 units of attribute alpha. Civilians that are physically affected by the bomb receive 20 additional units of attribute alpha. Ten units of attribute alpha are greater than the threshold that causes panic, so the panic behavior is triggered.

In addition to fear, the explosion awakens a need for the civilians to be calmed. In this simulation, calm is modeled by Pythagoras's "resource X." Civilians are considered consumers of this resource; police, fire, and medical personnel are modeled as suppliers of the resource.

(b) Panic. When civilians panic, their speed increases and they become aware of enemies (terrorists). Civilians want to run away from any terrorists they see and will continue to panic until their fear is removed and their calm is restored by police, fire, or medical personnel. First responders can remove fear (attribute alpha) by giving orders to move toward the triage points. These “orders” are a paintball weapon that decrease attribute alpha. In addition to taking away fear, first responders are suppliers of calm (resource X). When civilians are supplied with more than 25% of calm (resource X) and have less than 10 units of fear (attribute alpha), another alternate behavior is triggered: go to medical station.

(c) Go to Medical Station. When civilians cease panicking, they move to the nearest of the three medical stations set up outside the Celebrate Baltimore area. Civilians will continue to move to a medical station unless a terrorist interdicts them and makes them panic by giving the civilians additional fear (attribute alpha).

It is important to understand that the numbers associated with attribute alpha and resource X have been chosen to produce certain effects, and have no physical significance. The numbers are not as important as the relationship between the agents. In this simulation, police and terrorists have the same level of effect on civilians. Police are required to interact more with civilians that have been physically affected by the bomb. Also, police are required to do two things to stop civilians from panicking: they must assuage the civilians’ fear and calm them down.

b. Stretcher Wounded Civilians

After the explosion of the bomb, civilians that are stretcher wounded follow the events depicted in Figure 14.

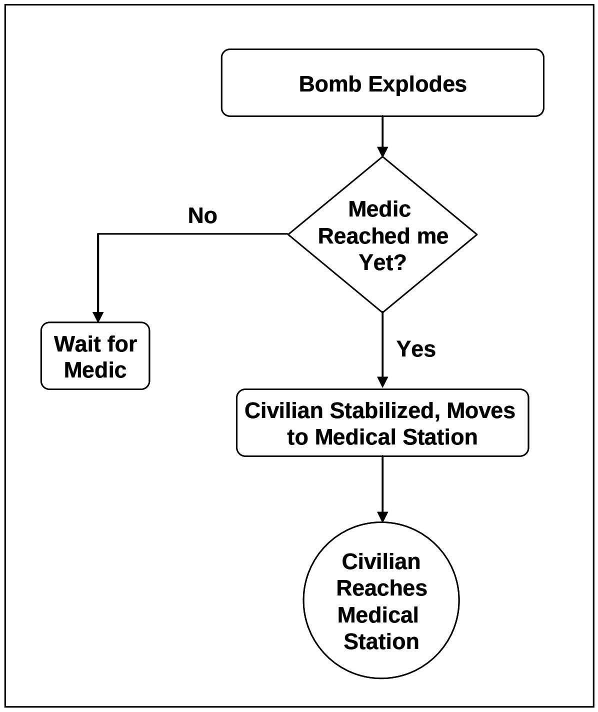


Figure 14. Flow Chart of Stretcher Wounded Civilian Activity

At timestep one, the bomb explodes in Baltimore's Inner Harbor Amphitheater. Stretcher wounded civilians remain in one place after the bomb explodes; they cannot move until they are stabilized by medical personnel. EMTs come to the scene of the explosion from two hospitals. The EMTs stabilize the stretcher wounded personnel and move them to the triage point. Stretcher wounded civilians are not affected by the panic exhibited by other civilians because they are being carried on a litter and cannot otherwise move.

(1) Common Qualities. All civilian agents have eyes instantiated as sensors and voice as a communications device, as previously stated. Civilians do not carry weapons.

(2) Movement Rates. See Table 10 for a translation of Pythagoras-specific terms into values that are more familiar to us. The movement rates and the sensing information are data derived from AMSAA. The average speed that a stretcher wounded civilian can move after being stabilized is about 1 kph, or about the speed that a Soldier walks while under a heavy combat load.

Characteristic	Value (Pythagoras)	Tolerance (Pythagoras)	Value (Actual)	Tolerance (Actual)
Movement Rate*	2	3	1 kph	1.5 kph
Sense and Detect*	Eyes			
Communication	Voice			
Weapons	None			
Vulnerability (Man)	0.5	0		
Vulnerability (Woman)	0.75	0		
Vulnerability (Boy and Girl)	1.0	0		

*Derived from AMSAA data.

Table 10. Stretcher Wounded Civilian Characteristics

(3) Civilian Vulnerability. In this simulation, men, women, and children have different vulnerability levels. The specific assignment of vulnerability levels is not scientific. It is a demonstration that it is possible to assign characteristics to civilians that can highlight differences between men, women, and children in this situation. For this simulation, men have half the vulnerability value of children. Women are halfway between men and children.

(4) Movement Desires. Civilians of this class have one desire: move toward the medical triage point. Although the civilians want to get to the triage point, they cannot begin moving in that direction until visited by a medic. A stretcher wounded civilian's health is simulated by fuel. When the bomb explodes, they run out of fuel, so they cannot move. The medics from the hospital are fuel providers. It is only through an interface between the medics and the stretcher wounded civilians that the civilians are stabilized (receive their fuel) and are able to move to the triage point.

4. Terrorists

a. Agitators

(1) Priority of Work. Terrorist agitators have one goal: incite panic in the crowd after the explosion of the bomb. The agitators hide in buildings until after the explosion, then come out of the buildings and interact with the crowd. The agitators do not focus on individual people, but attempt to

cover as much ground as possible in the response zone, thereby maximizing their influence.

(2) Common Qualities. All terrorist agents have eyes instantiated as sensors and voice as a communications device.

(3) Movement Rates. Movement rates and the sensing information are data derived from AMSAA. Terrorists move at an average speed of 4 kph, or at about the pace of an average walk. The maximum speed that a terrorist can move is 16 kph, or approximately running speed.

(4) Weapon. Terrorist agitators have a paintball weapon that increases the target's level of attribute alpha, which corresponds to fear in this simulation. One shot of the weapon provides enough fear to cause the civilians to panic.

(5) Simulating Covert Operation. By using the ability of agents in Pythagoras to change colors, it was possible to enable the agitators to "hide" in the crowd. Table 11 illustrates the use of color as a "hiding" mechanism for the agitators. At the beginning of the simulation, the agitators consider everyone to be an enemy; however, the civilians and police consider the agitators to be friendly. As an agitator starts to cause panic, he gradually changes color. After five shots, first responders and civilians are able to identify the agitator as an enemy. This gradual color change provides the effect that it may take the police some time to determine who is causing trouble.

	Red	**Green**	**Blue**	**Civilians**	**Hospital**	**Police**
Agitator (Start)	155	150	0	Friend	Friend	Friend
Agitator (after 1st shot)	165	120	0	Friend	Friend	Friend
Agitator (after 2nd shot)	175	90	0	Friend	Friend	Friend
Agitator (after 3rd shot)	185	60	0	Friend	Friend	Neutral
Agitator (after 4th shot)	195	30	0	Neutral	Friend	Neutral
Agitator (after 5th shot)	205	0	0	Enemy	Enemy	Enemy
Civilians	0	205	0		Friend	Friend
Hospital	0	220	205	Friend		Friend
Police	0	220	215	Friend	Friend	

Table 11. Terrorist Agitator Color Change

Read Table 11 as follows: The agent in the column sees the agent in the row in the manner of the intersecting cell. For example, Civilians see Agitator as a friend at the start of the simulation. Civilians see Agitator as neutral after shot four. Civilians see Agitator as an enemy after shot five.

b. Gunman

(1) Personality and Priority of Work. The terrorist gunman's goal supports the agitator goal of causing panic. The gunman will hide in a building until the first responders have arrived on the scene, then attack first responders and civilian targets of opportunity.

(2) Common Qualities. All terrorist agents have eyes instantiated as sensors and voice as a communications device.

(3) Movement Rates. Movement rates and the sensing information are data derived from AMSAA. When calm, terrorists move at an average speed of 4 kph, or at about the pace of an average walk. The maximum speed that a terrorist can move is 16 kph, or approximately running speed.

(4) Weapon. The gunman carries an AK-47 Assault Rifle. Weapon capabilities were derived from data supplied by AMSAA.

(5) Terrorist in Hiding. The gunman is able to hide by programming his base behavior so he is completely concealed, does not move, and therefore is undetectable. After the first responders are involved in tending to the situation (approximately timestep 375; 25 minutes in actual time), a behavior is triggered in the gunman to attack emergency services. During his attack, he is visible, armed, and has the desire to attack the enemy, but not get too close. This rule of engagement simulates the effect of a sniper.

5. Police

This section includes modeling decisions that reflect the author's determination of possible priorities of work for emergency first response organizations. Although the author has experience in crisis management planning at the military installation level, he established priorities of work entirely without the use of Baltimore standing operating procedures, or consultation with Baltimore officials. This simulation is not intended to specifically replicate Baltimore emergency response. TTPs may exist that are more effective than those established in this simulation. The purpose of this thesis is not to demonstrate the author's knowledge of crisis response TTPs, but rather to show that it is possible to model reasonable emergency response procedures in a multi-agent environment.

In this simulation, police forces share similar characteristics. All police units except the SWAT team have the same movement rates, sensory ability, weapons, and body armor. The author will detail this information for the traffic police in Section 5.a., but will not repeat it for subsequent units. Communication ability is similar between units. Each unit uses a communication device that simulates a handheld radio. The members of each unit can communicate with each other, but cannot communicate with members of other units via handheld radio. Members of different units can talk to each if they are close enough to use the voice communication device.

a. Traffic Police at Intersections

(1) General Characteristics. Table 12 describes the characteristics of the police that are stationed at the intersections of major roads leading to the Celebrate Baltimore area.

Characteristic	Value (Pythagoras)	Tolerance (Pythagoras)	Value (Actual)	Tolerance (Actual)
Movement Rate*	7	7	4 kph	4 kph
Sense and Detect*	Eyes			
Communication	Handheld Radio and Voice			
Weapons	9mm Pistol, Medical Kit, Orders to Civilians			
Body Armor	Level III-A: Most Handguns, Some Small Rifles			

*Derived from AMSAA data.

Table 12. Characteristics of Traffic Police at Intersections

(2) Personality and Priorities of Work. Figure 15 illustrates the priorities of work for traffic police.

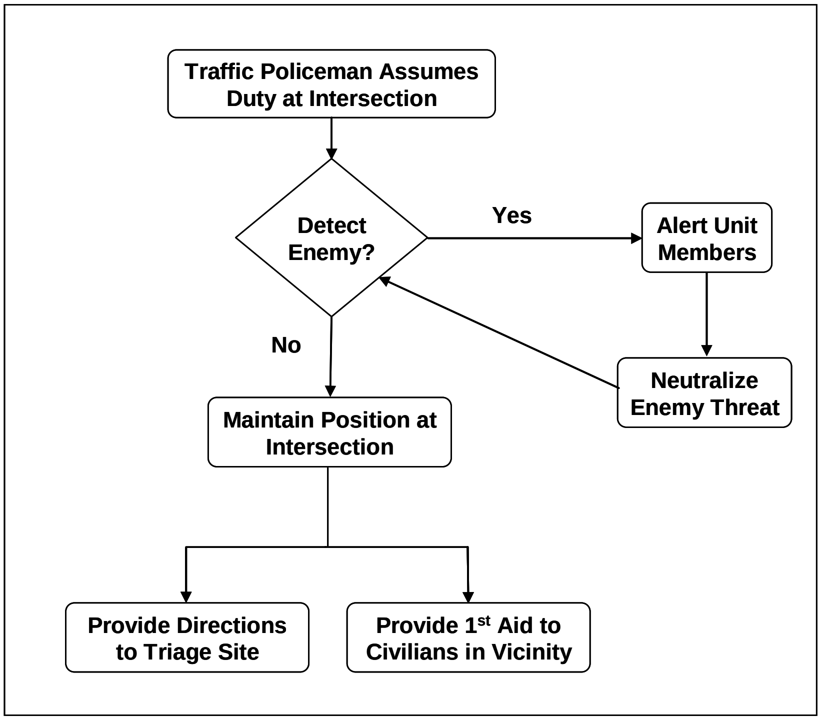


Figure 15. Priorities of Work for Traffic Police at Intersections

The author assumes that traffic police are on duty at the intersections leading into the Celebrate Baltimore area throughout the festival; that is, they are in position when the bomb explodes. In the simulation, traffic police maintain position in the immediate vicinity of their intersection, ensuring the crisis event is contained and chaos does not spread outside the immediate area. If traffic police see an enemy, they will alert the other members of the unit, attack the enemy, and neutralize the threat. When the threat is neutralized, the traffic police will then return to their initial intersection.

(3) Weapons and Body Armor. Police carry three tools that they can use to influence the agents around them.

(a) 9mm Semiautomatic Pistol. The 9mm pistol, in various forms, is the most commonly carried pistol in police units. The author used Army Field Manual 3-23.35 (*Combat Training with Pistols, M9 and M11*), the experience of subject matter experts, and personal experience as a military policeman to generate the characteristics of this weapon. Police are able to fire one shot using the 9mm every three timesteps, amounting to one aimed shot every 12 seconds of actual time. Maximum engagement range is approximately 82 pixels (50 meters).[40] Forty-five rounds is a common standard load for police to carry in a large city. A random damage degree of 0.25 means that 75% of the damage assessed to a target will be assessed deterministically, using the weapon's probability of kill. Twenty-five percent of the damage assessed is stochastic, based on a random number draw. Figure 16 shows the weapon's single shot probability of kill (SSPK), derived by multiplying the probability of hit and probability of kill, given a hit.

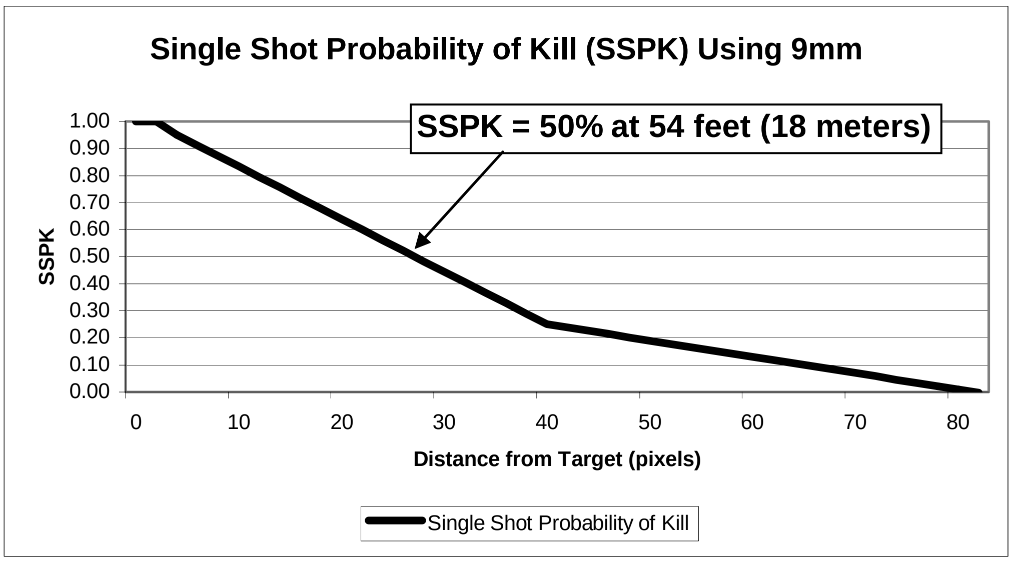


Figure 16. 9mm Single Shot Probability of Kill

(b) Medical Kit. The medical kit is a "restorative" weapon; i.e., its usage increases the target's health. Police can target unit members, friends, and neutral agents with the medical kit. When police use the medical kit to perform first aid on a civilian, the policeman is able to reduce the level of fear the civilian agent feels (by decreasing the level of attribute alpha). For the medical kit to be effective, the administering agent must be within a close distance to the target.

[40] United States Army, Field Manual 3-23.35, *Combat Training with Pistols, M9 and M11*, June 2003, pp. 1-2.

(c) Orders from Police. Orders are a “paintball” weapon whose usage causes a decrease in the target’s “fear,” i.e., a decreased level of attribute alpha. Police can target friends and neutral agents with the orders paintball weapon. Orders are effective to a distance of 100 feet (50 pixels).

(d) Body Armor. In this simulation, all police wear body armor that represents armor capable of stopping most handguns and some small caliber rifles. This body armor also provides protection against other threats, such as blunt force and slashing trauma. Body armor is simulated by reducing police vulnerability by 50%.

b. Police on Patrol

(1) General Characteristics. Patrolmen share the same general characteristics as the police at intersections described in the previous section. Patrolmen have one additional capability: they are a supplier of Pythagoras’s “resource X,” a measure of influence that will be described in detail later in this same section. Each patrol consists of two policemen.

(2) Personalities and Priorities of Work. Figure 17 is a diagram of the patrol areas in which the five patrols operate during the scenario. Patrols one and four circulate around their respective areas of operation in accordance with the patterns in Figure 17. Patrol number two stays in the area of the amphitheater because of crowd density. Patrols three and five have the same route, but cover it at different times.

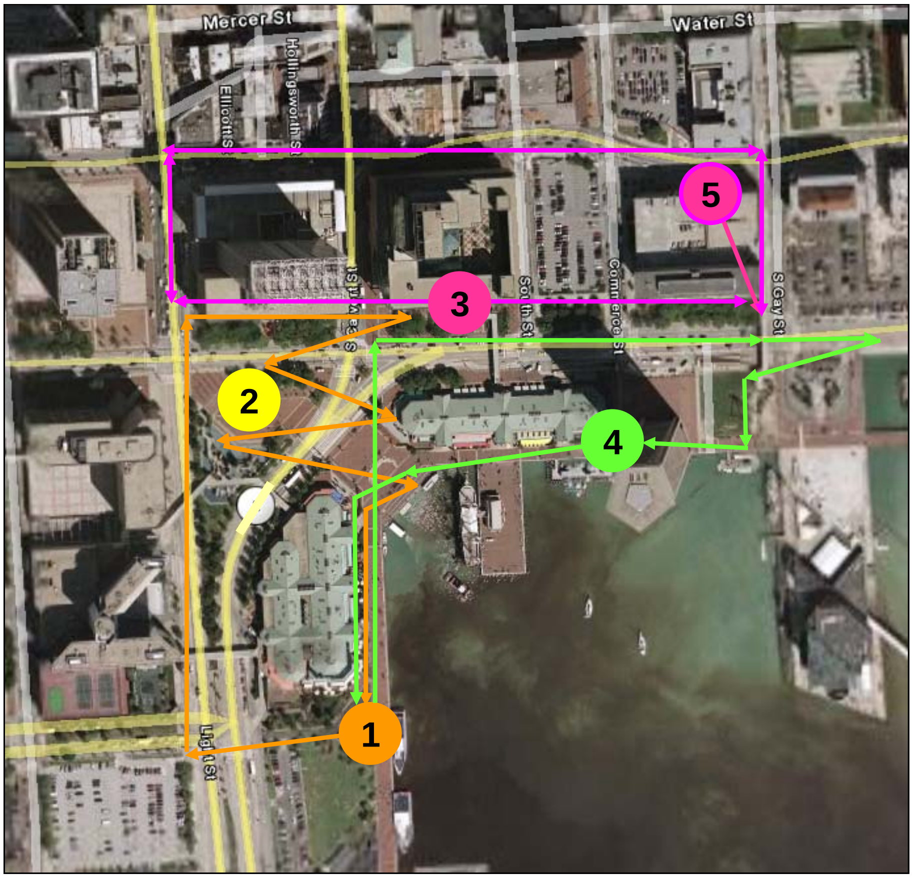


Figure 17. Police Patrol Areas

Figure 18 outlines the patrolmen's responsibilities and priorities of work throughout the simulation.

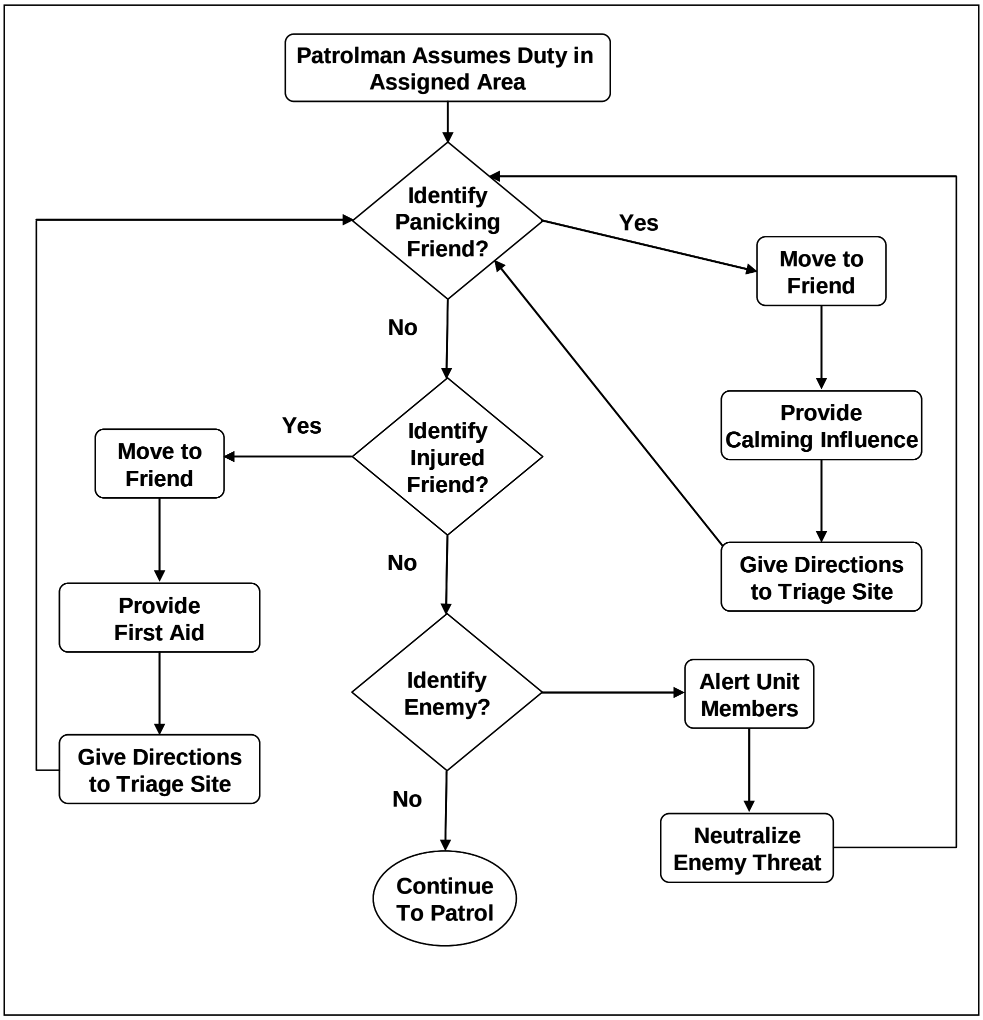


Figure 18. Priorities of Work for Patrolmen

In the case of police patrolmen, there are several competing priorities; the agent must "decide" which priority to address. In Pythagoras, the modeler facilitates this decision by assigning appropriate weights to the movement desires that correspond with a given priority. In this scenario, the patrolman's top priority is to calm panicking civilians, thereby restoring calm throughout the affected area. Tending to civilians that are already injured is of secondary importance. By calming the panicking crowd, the patrolman helps to ensure that more civilians are not injured. Enemy engagement is of tertiary importance because the SWAT team is alerted to engage the threat.

In this simulation, panicking civilians have two characteristics that alert the police of their state of panic:

- Low level of calm (Pythagoras's resource X)
- Raised level of fear (Pythagoras's attribute alpha)

Police patrols alleviate both of the above civilian conditions, enabling them to be relieved of their state of panic and move to the medical triage point.

Patrolmen are set up in Pythagoras as suppliers of resource X. As stated earlier, resource X in the simulation represents an objective measure of an agent's level of "calm." The Pythagoras model enables consumers of a given resource to notify suppliers when the consumer reaches a certain threshold, established in advance by the modeler. Suppliers receive the resource request from consumers and move to the consumers to impart the resource needed. In this simulation, the calmed civilian is given enough "calm" for the entire scenario, if not attacked by a terrorist. If the civilian is attacked by a terrorist, that civilian will panic again. Reversion to the panic behavior causes a loss of the resource, reinitiating the call for more. Patrolmen regenerate their supply of resource X; thus, they will not run out of the ability to calm civilians.

In addition to the ability to calm civilians using resource X, the patrolmen provide directions to a medical triage site and orders to go there. These orders are modeled as a "paintball" weapon, an influence tool that reduces the civilian's level of attribute alpha (fear). A civilian is considered calm as long as the civilian:

- Maintains a resource X level greater than 25% of maximum level
- Has an attribute alpha level lower than the amount imparted by one terrorist interaction

If there are no panicking civilians, the patrolman will attempt to identify wounded civilians. Upon identification of a wounded person, the patrolman will move to the wounded person and perform first aid. In this simulation, first aid is modeled with an influence tool that has restorative properties. When engaged with this influence tool, the target's health increases. After the target's health is restored, the patrolman will again try to identify if a civilian needs to be calmed. If not, the patrolman will seek to identify another wounded civilian.

Patrolmen will engage an enemy that they see if and only if their primary and secondary missions have been fulfilled. If the situation is such that the patrolman must engage an enemy threat, the weapon of choice is the patrolman's 9mm pistol. After the engagement, the patrolman will again check to see if a primary or secondary mission must be fulfilled. If not, and there are no additional enemies in sight, the patrolman will continue along the predetermined patrol route.

c. Follow-On Police

(1) General Characteristics. Follow-on police are police personnel that assemble at the Central District headquarters in response to the first alarm initiated by Baltimore's central dispatching authority. The characteristics of these personnel are the same as the traffic police and the patrolmen that were on station when the bomb exploded. Follow-on police enter the simulation as two teams of three policemen each. These teams arrive at intervals of 15 minutes (225 timesteps) after the explosion, starting at timestep 225.

(2) Priorities of Work. First-alarm police have similar goals to the patrolmen described in the previous section; the decision template diagram of Figure 18 applies. The follow-on patrols seek to spread a calming influence by clearing the buildings in the area surrounding the bomb blast and directing the people to the medical triage points. Figure 19 identifies one route that first-alarm police follow to provide assistance to the area affected by the bomb. The route shown illustrates a west to east path that is taken by one team of three personnel. The other team of three that is dispatched at the same time follows the same path, but in an east to west direction.

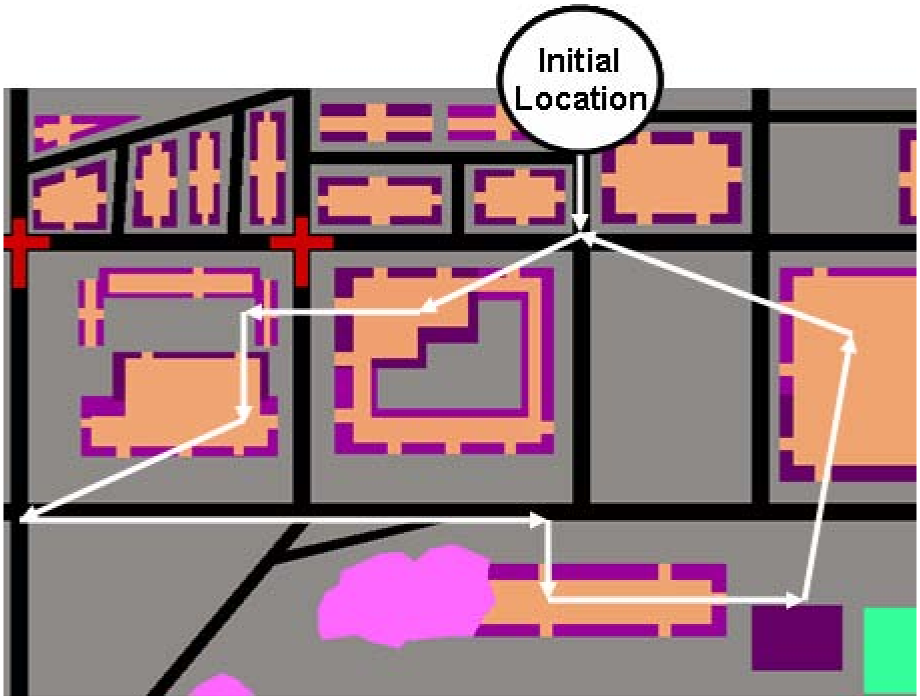


Figure 19. West to East Route of Follow-on Police

d. Incident Command Post (ICP)

(1) General Characteristics. The ICP is located in the convention center, directly to the west of the amphitheater. The purpose of the ICP is to provide situational awareness to the entire response force. It is through the ICP that the different organizations involved in the response know what each other are doing. The ICP is comprised of one leader from each of the organizations involved in the simulated response to this crisis:

- Traffic Police
- Initial Response Patrolmen
- Fire Department
- Hospital
- Central District Police (first-alarm, follow-on responders)
- SWAT Team

(2) Incident Command Structure. See Figures 20-22 for diagrams of the ICP's functionality.

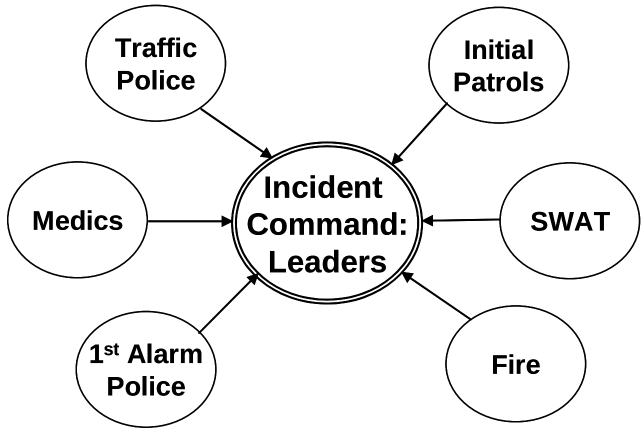


Figure 20. ICP Receives Information

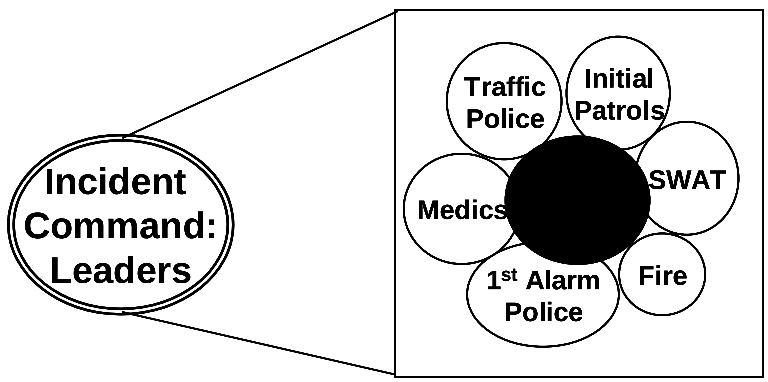


Figure 21. Information Sharing

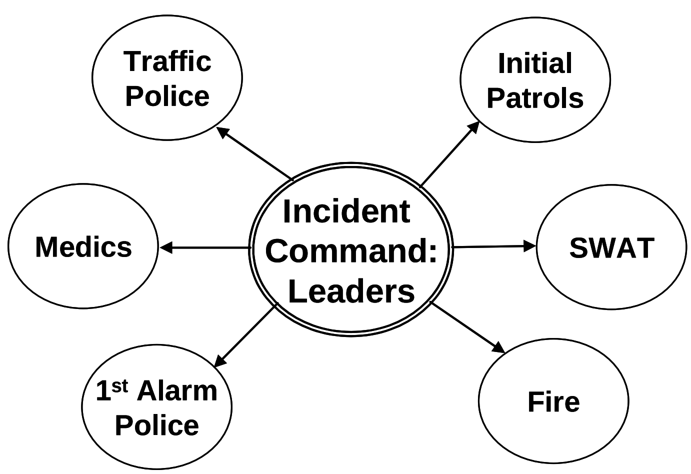


Figure 22. ICP Disseminates Information

The leaders that comprise the ICP receive information from the members of their individual organizations, using a communication device that simulates a standard handheld radio. The ICP is a well-connected organization, meaning that each member of the ICP has communication with every other member. Members of ICP communicate internally via a communication device that simulates a voice. After information is passed throughout the ICP, the leaders send the consolidated information back to the members of the organizations that are conducting the crisis response operations. In this manner, every member of every organization has situational awareness of the operational environment.

One example of the importance of the ICP is the identification of the terrorist gunman in this scenario. If a patrolman encounters the gunman, he is at a disadvantage; the patrol is armed with a pistol, the gunman with an AK-47. The patrolman communicates the location of the terrorist to the ICP. The ICP transmits that location to the SWAT team, which responds with nine personnel carrying M4 carbines, a decided advantage for the good guys.

e. SWAT Team

The SWAT team is located in the Central District headquarters, north of the bomb attack location. The mission of the SWAT team in this simulation is to receive information about the location of terrorists, move to that location, and neutralize the terrorist threat. After the threat has been neutralized, the SWAT team returns to the Central District headquarters to await another call. The team is comprised of nine police officers. These officers have sensory and communication characteristics that are similar to the other police officers described in this simulation. Table 13 outlines the characteristics of SWAT team members. SWAT team members have the capability to move faster than other police officers and they are more heavily armed. SWAT members carry a rifle in addition to their service pistol.

Characteristic	Value (Pythagoras)	Tolerance (Pythagoras)	Value (Actual)	Tolerance (Actual)
Movement Rate*	7	22	4 kph	12 kph
Sense and Detect*	Eyes			
Communication	Handheld Radio and Voice			
Weapons	M4 Carbine, 9mm, Medical Kit			
Body Armor	Level III-A: Most Handguns, Some Small Rifles			

*Derived from AMSAA data.

Table 13. Characteristics of SWAT Team

f. Firefighters

(1) General Characteristics. Firemen are initially located at two fire stations. Fire Station 23 is located approximate eight-tenths of a mile east of the location of the bomb blast. Fire Station 33 is located about three-quarters of a mile south of the blast. Table 14 includes the general characteristics of the firefighters in this simulation. In addition to the ability to provide first aid with the medical kit and direct civilians to the triage point, firefighters have the ability to stabilize stretcher wounded personnel and move them to the triage point. The mechanism for this action is described in detail in Section IV.A.5.g, which discusses medical personnel.

Characteristic	Value (Pythagoras)	Tolerance (Pythagoras)	Value (Actual)	Tolerance (Actual)
Movement Rate*	7	7	4 kph	4 kph
Sense and Detect*	Eyes			
Communication	Handheld Radio and Voice			
Weapons	Medical Kit, Orders to Civilians			
Body Armor	None			

*Derived from AMSAA data.

Table 14. Characteristics of Firefighters

(2) Priorities of Work. Firefighters deploy to the bomb attack area five minutes (75 timesteps) after the explosion occurs. Teams of five personnel deploy from their respective fire stations directly to the two buildings that sustain rubbling damage. Fire Station 23 moves to the northern rubble area. Fire Station 33 moves to the southern rubble area. The firefighters' mission is to search the rubble for survivors of the blast. Upon identification of

survivors, the firefighters have the capability to provide the level of medical support that a survivor needs, from first aid (using the medical kit, as described earlier) to stabilization of stretcher wounded civilians (described in detail with discussion of hospital personnel in the next section). Upon stabilizing the civilians, firemen will order them to a triage point. Through the interaction between firefighters and civilians, calm is restored and panic reduced in the same manner as with police interactions described earlier.

g. Medical Personnel

(1) General Characteristics. Medical personnel are initially located at two hospitals. Mercy Medical Center is located approximately nine-tenths of a mile north of the location of the bomb blast. Saint Johns Hopkins Hospital is located about two miles northeast of the blast. Table 15 includes the general characteristics of the medics in this simulation. In addition to the ability to provide first aid with the medical kit and direct civilians to the triage point, medics have the ability to stabilize stretcher wounded personnel and move them to the triage point.

Characteristic	Value (Pythagoras)	Tolerance (Pythagoras)	Value (Actual)	Tolerance (Actual)
Movement Rate to Area*	50	16	27 kph	11 kph
Movement Rate (Treatment)	1	0	0.5 kph	0
Sense and Detect*	Eyes			
Communication	Handheld Radio and Voice			
Weapons	Medical Kit, Orders to Civilians			
Body Armor	None			

*Derived from AMSAA data.

Table 15. Characteristics of Medical Personnel

(2) Treatment of Stretcher Wounded Civilians. After the bomb explodes, many civilians in the immediate area of the blast are critically wounded. Their wounds are serious enough that they cannot be stabilized by a policeman with standard shift equipment. In this simulation, only a trained agent (from a hospital or fire department) has the training and equipment needed to stabilize a stretcher wounded civilian. When an EMT identifies a stretcher

wounded civilian, the EMT moves to the civilian and provides treatment. Following the treatment, the civilian is moved to the triage point.

The author uses Pythagoras's concept of fuel to simulate the treatment of people who are unable to move due to their injuries. The use of fuel is similar to the police force's use of resource X to restore calm in panicking civilians. Stretcher wounded civilians cannot move because they are consumers of fuel and have run out. In this simulation, only EMTs are suppliers of fuel, so only EMTs can effectively treat stretcher wounded civilians. When a stretcher wounded civilian is short on fuel, that agent will request fuel from the supplier. The supplier will move to the consumer and provide the fuel. At that time, the consumer will begin moving in accordance with their desires.

There is no mechanism in Pythagoras to simulate one agent carrying another. After being stabilized, the stretcher wounded civilians move to the medical triage point under their own power; the speed is comparable to a soldier who is moving under heavy combat load. Speed under heavy combat load (2 kph) is approximately the speed that trained personnel would carry a stretcher. To simulate the EMT carrying the stretcher, the speed of the EMT is reduced to only 0.5 kph. If the EMT was actually carrying the stretcher, that agent would not be able to provide treatment to another patient until the first patient was dropped off and the EMT returned to the scene. This effect is accounted for in the simulation because the EMT's movement is slowed dramatically; i.e., due to the slow movement, the EMT has an appropriate lag time between treatments.

It is well known, well established, and often repeated that "all models are wrong, but some are useful."[41] The previous pages have been a discussion of how the author simulated several effects that capture the essence of emergency first response to a crisis event. There are some limitations to this model and modeling technique. The next section discusses the limitations

[41] George Box, "Robustness in the Strategy of Scientific Model Building," in Robert Launer and Graham Wilkinson (Eds.) *Robustness in Statistics*, 1979, p. 202.

identified, the artificialities associated with this type of simulations, and the assumptions made to work around those artificialities.

B. MODEL LIMITATIONS AND ARTIFICIALITIES

1. Model Limitations

It is important to note that the Pythagoras model is currently a beta version. The developers of the model have been particularly helpful in trying to provide a quality model to use for this thesis and others that are ongoing.

a. Invulnerable Agents

As mentioned previously in the discussion of timestep selection, agents jump from pixel to pixel with each timestep. It is possible for an agent to jump into a terrain feature from which the agent cannot move. For example, if an agent is standing next to a feature with movement factor 0 (e.g., a wall) and that agent has a desire to move past the wall, that agent may jump into the wall. The agent can no longer move because the feature's movement factor is 0.

This problem is especially noticeable in the event that a terrorist being tracked by a police patrolman jumps into a wall. The patrolman sees the terrorist's last position and sees the place at which the terrorist went into the wall. The patrolman will continue to engage the terrorist, even though he cannot see him, due to the wall having a concealment factor of 1.0. Since the wall has a protection factor of 1.0, the terrorist cannot be killed. The result is that the patrolman remains at the wall until the end of the simulation. In addition, the patrol communicates with his unit members, relaying the enemy's location, resulting in the entire unit being stationed at the wall, shooting ineffectively at the wall, for the rest of the scenario. This problem does not occur frequently enough to impact the analysis.

b. *Use of Fuel*

The modeler can use the concept of fuel in Pythagoras in several ways, one of which is actually using it as fuel. One limitation of Pythagoras is the mechanism by which fuel is passed from the supplier to the consumer. The supplier provides all of the necessary fuel in one timestep and then moves to the next consumer. This situation is an accurate representation of the supplier/consumer relationship if the supplier is dropping off a bulk fuel package. There is no ability for a modeler to represent fuel being passed from supplier to consumer over time, e.g., pumped at a certain rate of units per timestep. In this simulation, fuel represented health. If there was a capability to simulate a rate of fuel transfer, the EMTs stabilizing stretcher wounded civilians would have needed to stay directly with their patient until sufficient fuel was provided.

This deficiency extends to the use of resources X, Y, and Z, which are modeled in the same manner as fuel in Pythagoras. The supplier/consumer exchange deficiency is reported to have been fixed in Pythagoras version 1.10.1, but this has not been verified by the author.

c. *Weapon Usage*

There are situations in the current simulation in which agents are targeted with weapons they should not be targeted with. For example, police are supposed to target only enemies with the 9mm pistol. Civilians are considered friends to the police force. Unfortunately, situations occur in which police target civilians with the 9mm and kill them. This occurrence is (fortunately) relatively rare and does not provide a significant impact on the Measures of Effectiveness (MOEs) of this thesis.

There are instances within the simulation in which weapons that are restorative actually kill. These isolated instances occurred when police used their orders, a paintball restorative weapon, to influence civilians. This occurrence is also rare and does not impact the analysis of MOEs in this research.

d. Injured Friend Identification

Currently, agents do not react appropriately using the move "toward injured friend" logic. In fact, this desire does not appear to work at all.

e. Identification of Undetectable Agents

Prior to timestep 375, the terrorist gunman is in a state that sets his detection factor across all sensing bands to be 0.0. Within the vignette, there are several instances in which the terrorist gunman is identified when he should be completely undetectable. This model deficiency did not impact analysis because as the gunman was identified, appropriate action took place, i.e., location was communicated to friendly units, the friendly units consolidated and killed the terrorist(s).

f. Error Reporting

Error reporting in Pythagoras is not user friendly. If there is an error in the Pythagoras Java code, a generic error message appears on the screen and the scenario file will not open. The next step for the user to follow is to open the .xml file in an xml editor and look for errors. The user is not given an indication where to look in the code for the error. Heuristics exist to guide the user in looking through the code, but often fail. There are times that a working file is compared to a nonworking file and the differences should not cause errors in running the file. It would be useful for the developers of Pythagoras to provide an error message that directs the user to the specific area of computer code that fails in a model run.

2. Artificialities

a. Terrain

(1) Rubbling. The rubbling in this simulation was created without the use of scientific data. The author created the rubble to capture the effect of firefighters moving to the area and searching.

(2) Bomb Damage. In reality, a 7,300-pound bomb would have damaged more than two buildings. The desired effect of this simulation was to capture first responder interaction with the civilian crowd that was close to the explosion. This effect was captured in a satisfactory manner without detailed research into building structure thresholds.

(3) Triage Points. Due to the static nature of the Pythagoras terrain, triage points had to be set up before the simulation started. The assumption that the author made in using prepositioned triage points is that the location of these points was establish in pre-event planning.

b. Civilian Effects

Not addressed in this simulation are the unpredictable effects of crises on humans. Inevitably, there are civilians who will try to perform first aid on wounded people, help carry stretchers, and seek the opportunity to help the first responders. Also apparent, with the events surrounding the response to the 2005 hurricanes, is that some people will take advantage of the situation by becoming unruly, or even engaging in criminal activity. Neither effect is simulated in this vignette.

This chapter provided a detailed, step-by-step discussion of the technique used to model emergency response to a crisis in a MAS. The modeling described here corresponds to steps 8 and 9 of the methodology outlined in Figure 6 and subsequently discussed. The following chapter details steps 10 and 11 of Figure 5, identifying factors of concern and their levels. Chapter V will also discuss the experimental design process—the bridge between implementing the model and analyzing the data.

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V. EXPERIMENTAL DESIGN METHODOLOGY

This chapter describes steps 11 and 12 of the simulation methodology depicted in Figure 6, outlining the design of experiments (DOE) for this research. The DOE is the mechanism the analyst uses to vary input factors, conditioning the model to answer questions of interest; it is the bridge between model development and analysis of data. The author will describe the three different experimental designs chosen to collect the data needed to analyze the TOPOFF scenario. Following the discussion of the DOE and input factors, the author will describe the chosen MOEs that answer the questions posed at the beginning of this research. The chapter concludes with a brief discussion of tools and techniques that support the development of the DOE and the analysis of the resultant data.

A. METHODOLOGY

The power of simulations, especially MAS, results from the ability of an analyst to quickly analyze the consequences of decisions. In the case of emergency response, the decision may include the mix of response personnel and the time at which they are committed. The decision may also be less tangible, such as a recommendation on TTPs for a response organization. Gaining insight into these questions requires testing the given scenario by varying specific factors of interest over a range of values. This model, or another model that seeks to emulate human behavior, is stochastic; i.e., it involves variability. The stochastic nature of this model results in the necessity of running multiple replications of each unique model setting to obtain an empirical distribution of the range of possible responses.

The number of possible variables in this simulation is staggering; it highlights the need for an efficient DOE. There are three “sides” in this simulation: civilians, first responders, and terrorists. See Table 16 for a breakdown of the total number of unique agents in this simulation.

Side Name	First Level Subset	Number of Sub Levels	Total Number of Unique Agents
Civilian	Walking, Stretcher Wounded	2	8
First Responder	Police, Fire, Medical	3	46
Terrorist	Agitator, Gunman	2	5

Table 16. Agent Side Breakdown

Each unique agent class has several qualities that can be varied:

- Number of agents
- Vulnerability of agents
- Agent marksmanship (police and terrorist)
- Agent communication effectiveness

In addition to varying individual agent qualities, it is possible to vary overall qualities associated with several agents at once. For example:

- Effectiveness of a weapon in general, 12 weapons in the simulation (versus marksmanship of an individual agent using that weapon)
- Probability of successful communication of a given piece of equipment, nine different communication devices (versus an individual's effectiveness in using the device)
- Probability of detection for the sensor

From above, the total possible number of factors that can be varied in this simulation is 258.

	59 unique agents x 4 factors per agents	=	236 factors
+	12 different communication devices	=	12 factors
+	9 different communication devices	=	9 factors
+	1 sensor	=	1 factor

Of the 258 possible factors, the author determined that varying 48 factors would provide the data to answer the research questions posed. Using a simple grid design, varying these 48 factors at three levels (a high level, medium level, and low level) would result in 3^{48} (7.98×10^{22}) unique model runs or design points. Each model run takes approximately 40 minutes, resulting in a need for 5.32×10^{22} CPU hours. This simulation is a stochastic simulation, meaning that the analyst must run several replications of each design point to achieve meaningful results. Assuming that 30 replications are sufficient (many simulations require 50 or 100), the entire simulation would require 1.60 x 10^{24} CPU hours, which is about 116 trillion times the approximate age of the universe.[42]

Given that we do not have that long to wait, it is necessary to develop a much more efficient DOE than the traditional gridded design, or consider far fewer factors. The author chose to find an efficient design. Robust, efficient designs of experiments enable analytical factor selection, causing the resulting analysis to be less affected by personal judgments and bias.

The search for an efficient DOE quickly led to work done by U.S. Army Lieutenant Colonel Thomas M. Cioppa, using NOLHs. As mentioned earlier, data farming provides a method to take advantage of efficient DOEs, such as the NOLH, and supercomputers to grow an abundance of data points for further exploration. The NOLH design efficiently searches the high-dimensional input space defined by an intricate response surface. The NOLH has the following characteristics:[43]

- Approximate orthogonality of all input factors
- A collection of experimental cases representative of the subset of points in the hypercube of explanatory variables (space filling)
- Ability to examine 20 or more variables efficiently
- The flexibility to analyze and estimate multiple effects, interactions, and thresholds
- Requires minimal *a priori* assumptions on the response
- Easy design generation
- Ability to gracefully handle premature experiment termination

[42] Age of the Universe. Retrieved on 19 May 2006 from the World Wide Web at http://en.wikipedia.org/wiki/Age_of_the_Universe, using NASA's Wilkinson Microwave Anisotropy Probe (WMAP).

[43] Thomas M. Cioppa, "Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models," Ph.D. Dissertation, Operations Research Department, Naval Postgraduate School, Monterey, CA, 2002.

Refer to Cioppa's dissertation for additional information regarding a NOLH. Cioppa's algorithm requires only 2,049 design points to analyze the same solution space addressed by the previously mentioned gridded design! Instead of 3^{48} runs, we require $2^{11}+1$ runs, saving orders of magnitudes in computing time. With this design, it is possible to execute the DOE with a sufficient number of replications to achieve statistical relevance, using current technology, in a reasonable amount of time. See Appendix B (Design of Experiment Modeling) for detailed information about calculating the number of runs required.

Cioppa's is an excellent design, but current work ongoing by U.S. Army Lieutenant Colonel Alejandro Hernandez extends the ideas developed by Cioppa. Hernandez uses a method incorporating FRLHs to create experimental designs that are even more efficient than Cioppa's.

Hernandez found that using correlation reduction methods, it is possible to create a design that meets Cioppa's criteria for near orthogonality when the number of design points is greater than or equal to 49. In fact, the number of design points need only be greater than or equal to about three times the number of variables to maintain Cioppa's criteria of near orthogonality, see Figure 23.

n := number of design points (levels)
k := number of variables

When $n \geq 49$,
$$n \geq 3k$$

Figure 23. Relationship Between the Number of Variables and the Number of Levels in Hernandez's Design of Experiments

The result of Hernandez's work is the requirement for *only 144 design points* to complete a nearly orthogonal main effect design of experiments that will provide insight into the behavior of this problem's response surface, in 48-dimensional space. This 144 x 48 design represents a possible savings of *over 93%* in terms of design points and required computing power!

The benefits that result from using Hernandez's design come with costs that should be understood. This design is less space filling than designs using Cioppa's and Ye's[44] NOLH and OLH designs. In addition, the designs by Cioppa and Ye guarantee orthogonality or near orthogonality with the inclusion of one interaction or one quadratic term. Hernandez does not yet make that guarantee with his designs.

B. EXPERIMENTAL DESIGNS

1. Flexible Random Latin Hypercube Design (FRLH)

The author completed two separate experiments using the FRLH design. For both experiments, the hypercube generated by Hernandez was crossed with a simple 3 x 1 grid that captures three different probabilities of communication. The probabilities of communication examined are: 100%, 75%, and 50%. At 100%, a piece of information successfully passed between agents is certain to be received. At a level of 50%, the piece of information is passed with probability one-half. See Tables 17-19 for the factors varied in both FRLH experiments.

Factor Name	Low Level	High Level	Desired Outcome from Varying Given Factor
Number of Civilians (Integer)*	81	244	Identify possible effect of first responder to civilian ratio
Civilian Vulnerability (Continuous)	0	1	Identify effect of increased civilian susceptibility to terrorist action
Desire of Civilians to Avoid Terrorists (Continuous)	0	1	Examine effect of civilian fear of terrorists

*12 correlated factors.

Table 17. Civilian Factors Varied in FRLH Design

[44]K.Q. Ye, "Orthogonal Column Latin Hypercubes and their Application in Computer Experiments," J*ournal of the American Statistical Association – Theories and Models*, Vol. 93, No. 444, pp. 1430-1439, December 1998.

Factor Name	Low Level	High Level	Desired Outcome from Varying Given Factor
Number of Terrorists, Location 1 (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for terrorists
Number of Terrorists, Location 2 (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for terrorists
Number of Terrorists, Location 3 (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for terrorists
Number of Terrorists, Location 4 (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for terrorists
Number of Terrorist Gunmen (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for terrorists
Vulnerability of Agitators (Continuous)	0	1	Identify effect of terrorist body armor
Vulnerability of Terrorist Gunmen (Continuous)	0	1	Identify effect of terrorist body armor
Marksmanship of Agitators (Continuous)	0	1	Capture effect of agitator effectiveness in inciting panic
Marksmanship of Terrorist Gunmen (Continuous)	0	1	Capture effect of attriting first responder forces
Lethality of Bomb (Integer)	0	10	Identify possible effects of bomb strength

Table 18. Terrorist Factors Varied in FRLH Design

Factor Name	Low Level	High Level	Desired Outcome from Varying Given Factor
Number of EMTs from St. Johns Hopkins (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for first responders
Number of EMTs from Mercy Medical (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for first responders
Number of Patrolmen, Patrol Area 1-5* (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for first responders
Number of Follow-on Police at 15 minutes (Integer)	0	7	Determine importance of time in follow-on response
Number of Follow-on Police at 30 minutes (Integer)	0	7	Determine importance of time in follow-on response
Number of Follow-on Police at 45 minutes (Integer)	0	7	Determine importance of time in follow-on response
Number of Traffic Police, Areas 1-12** (Integer)	0	7	Identify possible effect of terrorist to police ratio; key terrain for first responders
Number of Personnel on SWAT Team (Integer)	5	15	Examine impact of SWAT team in current posture (waiting for call to attack)
Police Marksmanship (Continuous)	0	1	Examine importance of police effectiveness (against terrorist, for civilians)

*5 separately altered factors; **12 separately altered factors.

Table 19. First Responder Factors Varied in FRLH Design

There are two criteria that Cioppa uses to assess the orthogonality or near orthogonality of a design matrix comprised of each input variable (column) and design point (row). These two criteria are the absolute maximum pairwise correlation and the design matrix condition number.[45]

The absolute maximum pairwise correlation is computed by calculating the correlation between every pair of input columns in the design matrix, then taking the largest absolute value. A value of 0 is best, representing an orthogonal design matrix. A value of 1 is worst, meaning that at least 1 column is perfectly correlated with another column.

The condition number of the design matrix is used to "examine the sensitivities of a linear system." The condition number can also reveal the degree of nonorthogonality of a given design matrix. The best value possible for condition number is 1, associated with an orthogonal design matrix. Nonorthogonal design matrices have condition numbers greater than 1, meaning that the design matrix has a degree of multicollinearity.

The designs created by Hernandez for this research meet Cioppa's criteria for near orthogonality. One design consists of a 144 design points, and is described in detail in Section V.B.1.a. This design has an absolute maximum pairwise correlation of 0.008 and a condition number of 1.046. The second design is detailed in Section V.B.1.b. This design, consisting of 1,008 design points, has an absolute maximum pairwise correlation of 0.001 and a condition number of 1.006.[46]

a. Small FRLH Experiment

The first experimental run fully capitalized on the efficiency of Hernandez's FRLH design. This experiment involves the use of Hernandez's

[45]Thomas M. Cioppa, "Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models," Ph.D. Dissertation, Operations Research Department, Naval Postgraduate School, Monterey, CA, 2002.

[46]E-mail from LTC Hernandez titled "Roginski New Designs," 11 May 2006, office communication.

“base” design, using 144 design points, allowing for the possible use of 43 numeric factors and 5 qualitative factors (48 total factors). Based on a final analysis of the factors to be analyzed, the author used 37 of the 43 unique columns, and did not use the five qualitative factors. The effect of this decision on the design’s maximum pairwise correlation and condition number was to drive them lower, making the design even more nearly orthogonal.

The total number of runs in the small FRLH experiment is 144 x 15 x 3 (each level of communications grid), or 6,480 runs. The advantage of this experiment is its relatively short run time, when compared to the design discussed in the next section. The author received data back from the MHPCC in three days, versus a three week turn around time for the large experiment. The run resulted in approximately 4,320 rows and 5,310 columns of raw data for analysis.

The disadvantage of this design is that its sparse coverage of the solution space results in a much more granular understanding of the response surface. In situations which the response surface is complex, important detail may be missing from the data.

b. Large FRLH Experiment

The second experiment run was the largest, combining the efficiency of Hernandez’s FRLH design with the space filling nature of Cioppa’s design. The same 37 variables used in the previous experiment are used in this experiment; a heuristic approach was used to settle on 1,008 as the number of total design points.

The advantage of using this approach is the space filling nature of using over 1,000 design points. This number of design points enables much better coverage of the solution space than the 144 design point experiment, previously discussed. Greater coverage of the overall solution space results in a better understanding of the response surface, and less of a chance to miss an important result. The disadvantage of this design is that, while relatively efficient compared to a gridded design, this experiment still takes longer to run than the smaller FRLH design.

Using the output of previous runs, the author determined that 15 replications of each design point are sufficient for analysis of data. The total number of runs in the large FRLH experiments is 1,008 x 15 x 3 (each level of communications grid), or 45,360. This simulation requires 40 minutes of CPU time for each run; therefore, the expected length of this experiment was 30,240 CPU hours. The set of runs was completed with the help of the MHPCC supercomputers in about three weeks, resulting in approximately 45,360 rows and 5,310 columns of raw data for analysis.

2. Gridded Design

The author also used a gridded design, again run at the MHPCC. The intent of this design is to focus directly on a few factors, while holding the rest constant. The author considered the following variables and levels in this design (see Table 20). The total number of runs in the gridded experiment is 5^3 (three variables at five levels each) x 20 replications, or 2,500 runs of the simulation. The expected time for 2,500 runs at MHPCC was about 1,666 CPU hours. The author received data back from Maui in two days, versus a three-week turn around time for the large experiment.

Factor Name	Low Level	High Level	Step	Number of Levels	Desired Outcome From Varying Given Factor
Probability of Communication	0.1	0.9	0.2	5	Identify effect of communication equipment on response
Number of Traffic Police*	0	5	1	5	Identify effect of ratio of traffic police to terrorists, and to patrols
Number of Patrolmen**	0	5	1	5	Identify effect of ratio of patrolmen to terrorists, and traffic cops

*Each traffic location is given the same number; **Each patrol location is given the same number.

Table 20. Gridded Design Completed at MHPCC

3. Measure of Effectiveness

Analyzing a data set that is 45,000 rows by 5,300 columns or even 6,000 rows by 5,300 columns, is a bewildering task if the analyst lacks focus and scope. MOEs provide the scope and focus that the analyst needs to provide timely support to the decision maker. The analyst establishes MOEs that help provide insights and answers to research questions posed at the beginning of a given project. To understand the use of MOEs, it is important to understand the difference between MOEs and measures of performance (MOPs). Sections a and b below show the definitions of a MOP and MOE from the Defense Modeling and Simulation Office (DMSO).

a. Measure of Performance, Defined[47]

A measure of how the system/individual performs its functions in a given environment (e.g., number of targets detected, reaction time, number of targets nominated, susceptibility of deception, task completion time). It is closely related to inherent parameters (physical and structural), but measures attributes of system behavior.

b. Measure of Effectiveness, Defined[48]

A qualitative or quantitative measure of the performance of a model or simulation or a characteristic that indicates the degree to which it performs the task or meets an operational objective or requirement under specified conditions.

c. Use of MOEs

MOPs determine how well one small entity fared in the mission. MOEs identify how well the mission was accomplished overall.[49] Establishing

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[47] DMSO, definition of Measure of Performance. Retrieved 21 on May 2006 from the World Wide Web at https://www.dmso.mil/public/resources/glossary/results?do=get&search_text=MOP

[48] DMSO, definition of Measure of Effectiveness. Retrieved on 21 May 2006 from the World Wide Web at https://www.dmso.mil/public/resources/glossary/results?do=get&search_text=MOE

[49] Donald E. Brown, Ph.D., and C. Donald Robinson, "Development of Metrics to Evaluate

defensible MOEs is much more of a challenge than establishing interesting MOPs, especially in an area that may directly impact peoples' lives, such as emergency response.

For example, baseball fans compare their favorite players' batting average, on base percentage, and number of runs batted, to try to determine the better player. These are measures of the players' *performance*, not *effectiveness.* To measure a player's true effectiveness, we must ascertain how much that player contributes to winning the game, winning the division, or the World Series.[50]

As stated previously, MOEs are established to answer questions posed at the beginning of research. Below are the four MOEs selected for this research, followed by Table 21 that highlights the research questions associated with each MOE. The MOEs address the effectiveness of the first response agencies in mitigating the effects of the crisis event, seeking to achieve the following goals:

- Stabilize wounded civilians
- Restore calm in the area
- Eliminate further threats
- Maintain safety of first responders

MOEs

- **MOE 1.** The first MOE is the percentage of civilians that have not received sufficient medical treatment by the end of the first hour. This MOE directly addresses the first priority established above by

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Effectiveness of Emergency Response Operations," presented at the 10th International Command and Control Research and Technology Symposium, The Future of C2, June 2005. Retrieved on 2 December 2005 from the World Wide Web at www.dodccrp.org/events/2005/10th/papers/326.pdf

[50]Brian G. McCue, Christine A. Hughes, and Kathleen M. Ward, "Analysis Planning for Domestic Weapon-of-Mass-Destruction Exercise," The CNA Corporation, The Occasional Paper Series, (IPR) 10856, May 2003, pp. 21-22. Retrieved on 2 December 2005 from the World Wide Web at www.cna.org/documents/IPR10856_1.pdf

measuring the effectiveness of first responders in the "Golden Hour," or the first hour after the bomb blast.

- **MOE 2.** The second MOE is similar to the first in that it measures the effectiveness of the first responders. The second MOE is the percentage of civilians at the triage points at the end of the first hour. Civilians only go to the triage points after first responders have successfully interacted with them, provided aid, and assuaged their feeling of panic. This MOE highlights the success of first responders in achieving the second priority outlined above. It measures the first response force's psychological effectiveness on the civilians, where the first MOE measures physical effectiveness.
- **MOE 3.** The third MOE is the means that the analyst will use to determine success in achieving the third priority. The third MOE is the percentage of times among the replications for a given design point that all terrorist gunmen were neutralized. Total neutralization of the gunmen means there is no further lethal threat.
- **MOE 4.** The fourth MOE is the percentage of first responders injured or killed during response operations in the first hour. Using this MOE, the analyst can gain insight into the factors that are most important in determining survivability of first responders.

Research Question	MOE
What is an appropriate methodology for use of a MAS environment in the modeling of emergency response to the simulated VBIED that explodes near the amphitheatre in Baltimore's Inner Harbor?	Figure 6, Step 10
What is the most appropriate mix of police, fire, and medical assets?	1, 2
What is the most effective interagency communication architecture for emergency response to VBIED in Baltimore's Inner Harbor?	3, 4

Table 21. Research Questions and Associated MOEs

C. EXPERIMENTAL DESIGN TOOLS AND TECHNIQUES

Visual observation of the Pythagoras model provides a certain degree of value; however, the purpose of a MAS, such as Pythagoras, is to view a problem's high-dimensional space. People can see in three dimensions. With a degree of chart wizardry, one can argue that it is possible to gain an idea of four-or five-dimensional space. The response surface associated with this problem is in 40+ dimensional space, requiring the use of several different tools. This section describes those tools used in this research.

The tools bridging Pythagoras-produced data to the analysis conducted include spreadsheet modeling with Excel, Tiller©, and XML. As described in Chapter IV (Model Development) the author maintains that spreadsheet modeling provides an organized method to perform the thought process, while simultaneously cataloging important modeling parameters.

1. Spreadsheet Modeling with Excel

Appendix B, Section B, "DOE Spreadsheet Modeling," outlines the crossed FRLH DOEs, both large (1,008 design points) and small (144 design points). There are six spreadsheets.

1. The first is the factor description and is similar to that of Tables 17-19. It outlines both the decision[51] (associated with first responders) and noise[52] (associated with civilians and terrorists) factors creating the robust design.
2. The second spreadsheet is a FRLH coded spreadsheet for 40 factors detailing the factor levels used at each of the 1,008 design points in the large FRLH experiment.[53]
3. The third spreadsheet is a design file and looks very similar to the second. This file adds an additional 11 correlated factors. These are correlated to the civilian instance factors. The correlation represents an assumption that the author made in scaling all different classes of civilians to maintain the same proportionality as in the EPiCS simulation conducted by TRAC-WSMR. The design file incorporates the final crossed NOLH DOE with 3,024 design points.
4. The fourth spreadsheet is a FRLH-coded spreadsheet for 40 factors detailing the factor levels used at each of the 144 design points in the small FRLH experiment.[54]

[51]Decision Variable: Variable that can be controlled by a decision maker for first-response forces.

[52]Noise Variable: Variable that cannot be affected by first response decision makers.

[53]E-mail from LTC Alejandro Hernandez titled "Roginski Designs," sent 11 May 2006, office communication. FRLH 40 Factors, coded by LTC Alejandro Hernandez, Naval Postgraduate School, Monterey, CA.

[54]Ibid.

5. The fifth spreadsheet is a design file and looks very similar to the second. This file adds an additional 11 correlated factors. These are correlated to the civilian instance factors. The correlation represents an assumption that the author made in scaling all different classes of civilians to maintain the same proportionality as in the EPiCS simulation conducted by TRAC-WSMR. The design file incorporates the final crossed NOLH DOE with 432 design points.

6. The sixth spreadsheet results from Visual Basic code written by Major Chris Michel, USMC, that takes row data from the FRLH spreadsheets and put it in a format to be used later in the Tiller©. The author will describe this code in Section V.C.1.

2. Extensible Markup Language (XML)

Though Pythagoras offers an easily viewed GUI to input data values, analysts may also build Pythagoras scenarios and edit them using the XML, as all Pythagoras databases are stored and transmitted in XML. XML offers a simple and very flexible text format device derived from SGML (ISO 8879). Technicians originally designed SGML to meet the challenges of large-scale electronic publishing; XML also plays an increasingly important role in the exchange of a wide variety of data on the Internet.[55] Storing scenarios in XML permits the analyst to transmit scenario files quite rapidly over the Internet to perform data farming techniques. This process occurs with agencies such as the MHPCC and enables thousands of design points to run over a networked cluster of computers in a short amount of time.[56]

3. Tiller©

The Tiller, Version 0.7.0.0, Copyright 2004 Referentia Systems Incorporated, is a product developed in support of Project Albert and the Marine Corps Warfighting Laboratory. Its primary purpose is to prepare model

[55]W3C, Extensible Markup Language. Retrieved on 21 May 2006 from the World Wide Web at http://www.w3.org/XML

[56]Charles A. Sulewski, "An Exploration of Unmanned Aerial Vehicles in the Army's Future Combat Systems Family of Systems," Masters Thesis, Naval Postgraduate School, Monterey, CA, December 2005.

XML scenarios for data farming. The Tiller© outputs two files the user must submit together to execute a data farming job.

The first file is *basecase.xml*, which is the model scenario file. For Pythagoras models, the only change to the scenario file is in changing the name to *basecase*. The author identified that it can be more efficient to manually change the name of the scenario file, rather than use the file generated by the Tiller©. The file generated by the Tiller© can be up to 33% larger than the base scenario file, with no added functionality. The second file generated by the Tiller© is a usable *study.xml* file containing the chosen DOE for running at the MHPCC.

The Tiller© application may be used alone to process the DOE. The author used the Tiller's© *study.xml* file as a starting point from which to "lockstep" several values together. Lockstepping is the process by which several factors are changed, but some values are changed together. The result of submitting the altered study file was that the author changed 104 variables in each design point, using 37 different factors from Hernandez's FRLH.

4. Excel Interface by Michel

Major Christopher Michel, USMC, developed Visual Basic code that provides a bridge between the FRLH developed by Hernandez and the Tiller© developed by Referentia. The user copies XML code that defines each excursion to be run. Michel's code causes Excel to snap to the worksheet with the FRLH and copy a row of factors. Next, the program snaps to the worksheet that the user has prepared to receive the design points and transposes the factors into the appropriate cells. This process is repeated until the final row of the FRLH is placed into the spreadsheet. All that remains for the user to do is copy the first three columns of the worksheet and paste those cells into the *study.xml* file.[57] Refer to Appendix B, Section B (Excel Macro by Michel) to see the Visual Basic code.

This chapter outlined the procedures for completing steps 11 and 12 of the simulation methodology discussed in Figure 5, which discusses the efficient experimental design used in this research. The following chapter will demonstrate the accomplishment of step 13, the analysis of the data resultant from implementing the DOE.

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[57]Christopher Michel, "Supporting A Marine Air Ground Task Force With Appropriate Quantities of Ground Based Fire Support," Masters Thesis, Naval Postgraduate School, Monterey, CA, September 2006.

VI. DATA ANALYSIS

This chapter describes step 13 of the simulation methodology depicted in Figure 6, the analysis of data developed from executing the experimental design discussed in the previous chapter. It also addresses the tools and techniques used to collect and "clean" the data. Next, the thesis-based observations provide the analysis that answers our research questions. The insights into these research questions are summarized in the conclusions and recommendations for future study that comprise Chapter VII.

A. DATA COLLECTION AND CLEANING

1. Clementine

Clementine is a data mining software package that contains features used throughout most of the data cleaning process. Data cleaning is the process by which raw data from an experiment are transformed into a format and layout that is conducive to conducting analysis. To facilitate this process, and other data mining processes, Clementine provides a GUI-based suite that enables quick and easy manipulation of the initial data sets into manageable sets for analysis.

The feature of Clementine that was most important in data cleaning was the development of a data "stream" on the background palette.[58] A Clementine stream is an intuitive, graphical representation of a process on the computer screen. For example, this data cleaning process consisted of importing a data file, removing columns, changing column names to make data analysis more intuitive, and exporting the transformed data into another file. To repeat the process for another file, all that need happen is for the new file to be uploaded onto the palette, and then the stream attached to the new file. The new stream is executed and immediately cleaned. See Appendix C (Data Analysis) for an illustration of a Clementine stream used in this data cleaning process.

[58]Clementine product description. Retrieved on 30 May 2006 from the World Wide Web at http://www.spss.com/clementine

After all files from a given experiment were ready, the author imported the new files into Excel and inserted a column that identified the associated probability of communication for the given file. The new file was reloaded to the Clementine palette and appended to the other files that resulted from the experiment. This consolidated file was then exported into a file format to be analyzed with JMP Statistical Discovery Software™. The next section provides more information about JMP.

Clementine facilitated the data cleaning process for ten total files, in three separate experiments, resulting in the removal of nearly 52,000 columns of data from the files to be analyzed. In Clementine, this process took approximately three hours. Based on preliminary work in SPLUS, executing the same process in SPLUS would have taken twice as long, even with its new Big Data library feature. In JMP, the process would have consisted of 52,000 point and click deletions, taking much longer than even SPLUS.

2. Analysis Software Tools (JMP Statistical Discovery Software ™)

JMP Statistical Discovery Software™ contains the software features used for both the data cleaning and the data analysis portion of this research. The JMP statistics package is the tool chosen to support the majority of the data analysis because it is a useful statistical analysis tool with powerful data visualization features. JMP excels at helping analysts uncover relationships and outliers within the data. The exploration of these data points can lead to valuable discoveries and possible surprises in the data, thus supporting better decision-making.[59]

3. Analysis Techniques

Most large databases yield the flexibility to perform a wide array of data analysis techniques. Though this analysis applies statistical tests, the core

[59] JMP, The Statistical Discovery Software. Retrieved on 20 April 2006 from the World Wide Web at http://www.jmp.com/product/jmp5_brochure.pdf

analysis focuses primarily on two techniques: Classification and Regression Trees, and Multiple Regression.

a. Classification and Regression Trees (CART)

The CART (Classification and Regression Trees) algorithm is a widely used statistical procedure for producing classification and regression models with a tree-based structure. Tree models assist the analyst in the identification of significant factors, by grouping similar points into cells. This process is recursive; it repeats as many times as necessary so that each end branch defines a separate node.[60] [61] The regression tree yields a continuous output; however, classification trees are discrete in nature.[62] The CART algorithm will classify significant response factors into classes complemented by further regression analysis.[63]

Throughout this analysis, the author used a 5% heuristic to determine when to stop splitting the tree. As additional splits are made to the tree, the R^2 value is logged. Each R^2 value is compared to the previous value, when the change in R^2 is less than 5%, no further splits are made. The final split is then pruned, leaving only splits in the tree that make an impact on the R^2 of greater than 5%.

b. Multiple Regression

A general regression analysis is a statistical process that investigates the relationship between two or more variables (factors) related in a nondeterministic fashion. The objective in multiple regression is to build a

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[60]Douglas Montgomery, Elizabeth Peck, and Geoffrey Vining, *Introduction to Linear Regression Analysis,* Third Edition, (John Wiley and Sons, Inc., 2001), p. 516.

[61]David Hand, Heikki Mannila, and Padhraic Smyth, *Principles of Data Mining,* (MIT Press, Cambridge, MA, 2001), p. 145, 343.

[62]Hand, p. 147.

[63]Ibid 47.

probabilistic model that relates a dependent variable *y* to one or more independent or predictor variables. The actual *y* values in a sample differ from the predicted values. The errors or *residuals,* denoted by *e,* are the differences between the observed and predicted values, hopefully possessing a normal distribution with constant variances.[64] Regression analysis is practical for gaining insight on which predictor variables (design factors) have the greatest significance toward the success of the first response mission, as measured by the previously mentioned MOEs. Regression analysis is also useful in identifying interactions between input variables.[65]

B. RESEARCH QUESTION-BASED ANALYSIS

Each data set developed through the experimental design process contributed to the analysis described in this section. Because of data output difficulties at MHPCC, only two-thirds of the data from the small FRLH experiment was available for analysis, corresponding to the 144 design point base design, with probability of communication set at 1.0 and 0.75.

Before conducting analysis of the data using trees and regression models, the data were grouped by like design points. This model is stochastic and, as a result, each design point is replicated 15 times. Design points are grouped and desirable statistics taken (e.g., means of desired end of run MOEs).

For example, the raw data set for the small FRLH experiment resulted in 4,320 rows. The first MOE addresses the percentage of civilians injured after the end of the first hour. The data set is grouped by design point, and the mean number of civilians injured at the end of the first hour taken. The result of this approach is that the actual data set analyzed for a given problem is more manageable than when in its raw form. A data that is 4,320 rows by 170 columns (after cleaning) may be reduced to data set of 288 rows by 39 columns.

[64]Devore, p. 587.

[65]Ibid 47.

1. MOE 1. Percentage of Civilians Injured After First Hour

a. Flexible Random Latin Hypercube (FRLH) Experiment

The first step of this analysis was to develop a classification and regression tree to identify which variables have the greatest significance in determining the percentage of civilians injured. Figure 24 shows the increase in R^2 (a measure of the amount of variance in the data that is explained by the given model) with the number of splits in the regression tree, using data generated with the small FRLH model. Note that after the third split in the tree, there is only a small difference in R^2. The increase resulting from making four splits, versus three, is only 0.03, from 0.816 to 0.846, resulting in a well-fit regression tree.

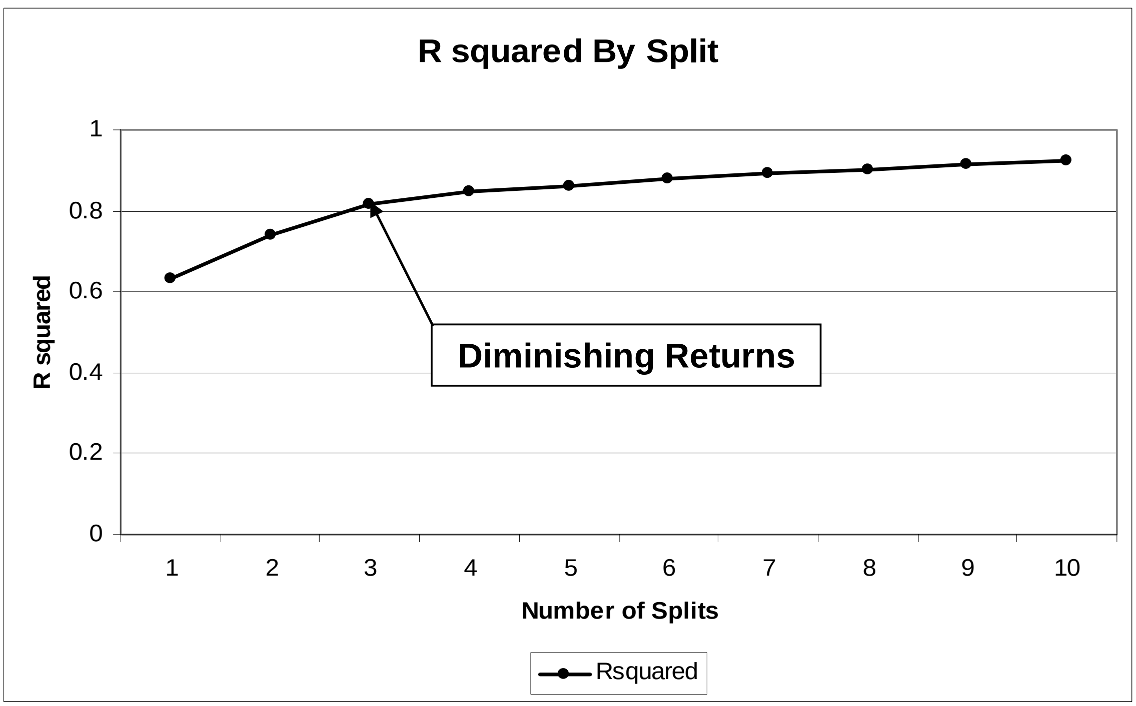


Figure 24. Analysis of R^2 by Regression Tree Split (Small FRLH Experiment, Response = Percentage of Injured Civilians)

Figure 25 is the regression tree developed in JMP to help gain insight into the factors that influence the percentage of civilians that remain injured after the first hour. As mentioned previously, regression trees involve the use of an algorithm that groups like observations together, maintaining the highest possible “purity.” After the completion of each step, the algorithm calculates the decrease in total sum of squares resulting from the introduction of each “candidate node.” See Appendix C (Data Analysis) for a more detailed description.

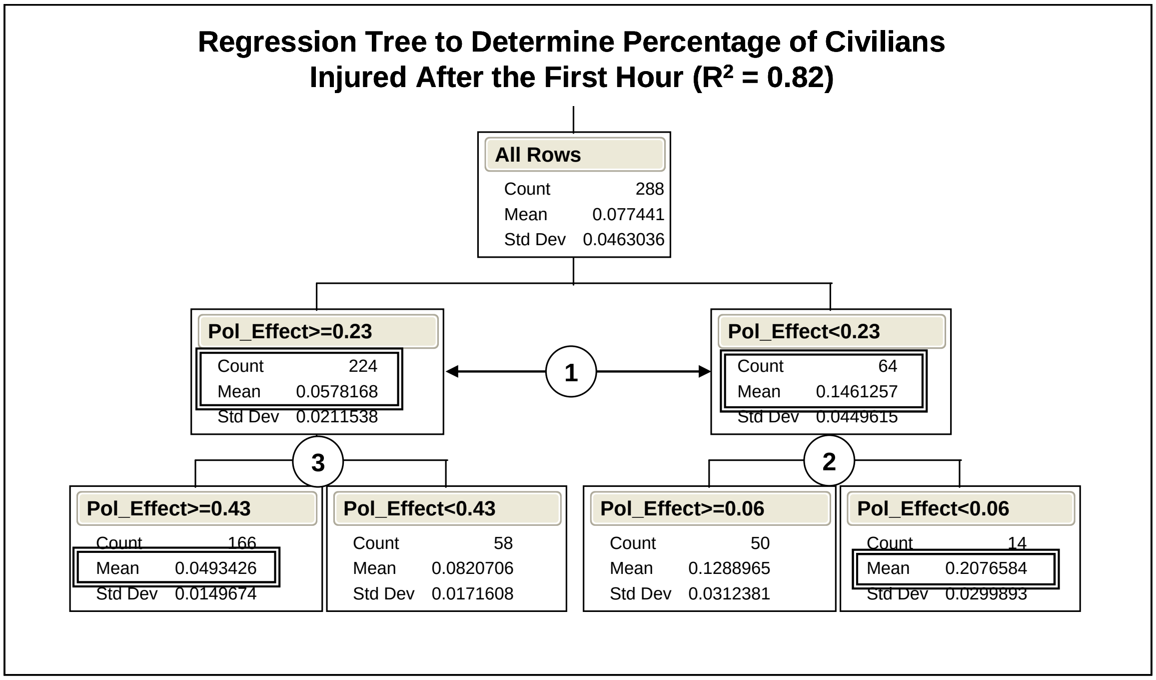


Figure 25. Regression Tree to Determine the Percentage of Civilians Injured After the First Hour (Small FRLH Experiment)

A strength of regression trees is their interpretability and ease of understanding. For example, see item one on Figure 25. Item one is the first split of the regression tree. JMP determined that the division in the data that would result in the greatest increase in purity would be to split the data using the variable “Police Effectiveness in Issuing Orders to Civilians.” In effect, this is the most important single variable in determining the number of injured civilians at the end of the first hour. The increase in purity corresponds to the greatest reduction in total sum of squares. The tree is used as follows.

- There are 64 design points that correspond to a police effectiveness score of less than 23%. For these cases, an average of about 15% of the civilians remain injured at the end of the first hour (see the boxed entry in the first split of the tree).

- There are 224 design points that have a police effectiveness score of greater than or equal to 23%. For these cases, an average of approximately 5% of the civilians remains injured after one hour.

Item 2 shows the second split in the tree, corresponding to the greatest reduction in total sum or squares for the observations in the node (Pol_Effect<.23). Notice that the worst case scenario in the tree results from this split. If the police effectiveness is less than 6%, we would expect to see an average of about 20% of the civilians that remain at the end of the first hour.

Item 3 shows the third split in the tree, corresponding to the third largest reduction in total sum or squares for the model. Notice that the best case scenario in the tree results from this split. If police effectiveness is less than 23%, and greater than 43%, we would expect to see only about approximately 4% of the civilians injured at the end of the first hour.

It is interesting that, after considering all 37 independent variables, the most important variable in determining the number of injured civilians is a variable that the decision maker can control; it is a decision variable. However, the variable that has the second most impact is a variable which the decision maker cannot control, a noise variable—the desire of civilians to flee from the enemy. This variable is not displayed on the tree; it is the second variable to appear if the tree is expanded. This desire may correspond to a feeling of terror in identifying the enemy that is greater than the comfort offered by a first responder. The injured civilian runs away and the first responder is not able to help.

It is helpful to understand that there is a certain degree of randomness that prevails in our world. A decision maker will mostly likely not be able to remove all uncertainty from a crisis response plan. It is helpful to understand the relationship of controllable factors to uncontrollable factors. The contour plot in Figure 26 helps demonstrate the relationship of our decision factor (police effectiveness) to the noise factor (desire to flee).

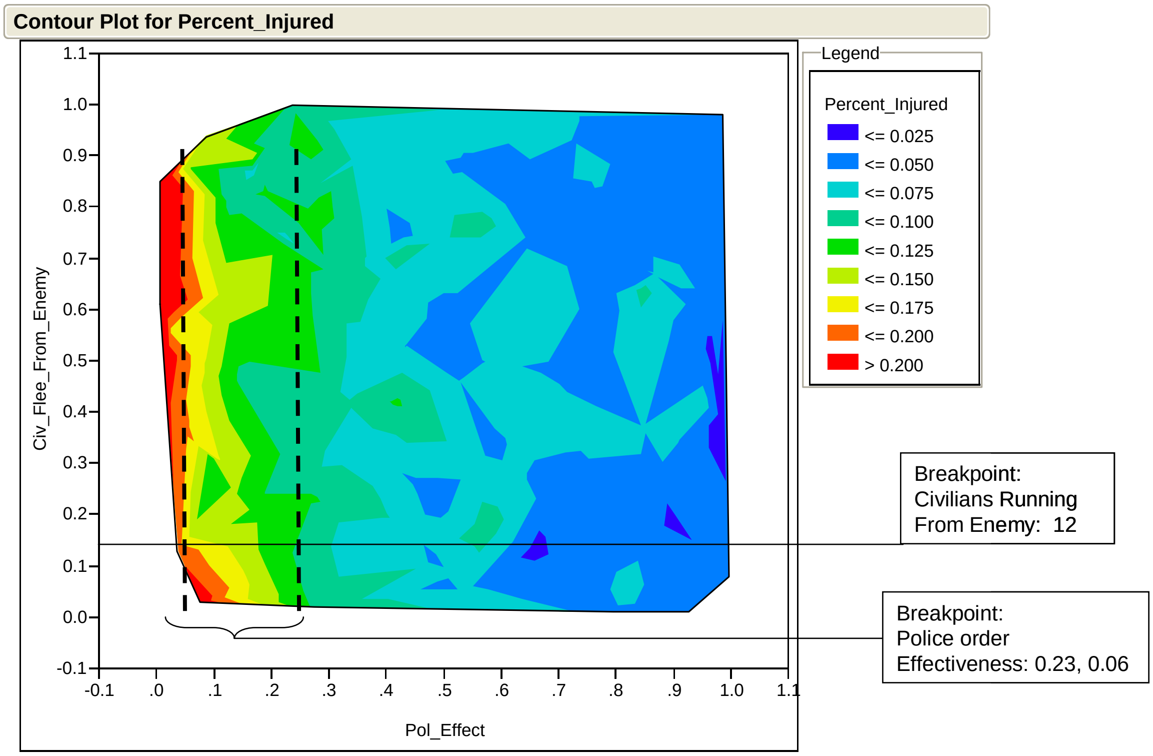


Figure 26. Relationship of Police Effectiveness in Giving Orders to Number of Civilians in Determining Percentage of Injured Civilians (Small FRLH Experiment) (best viewed in color)

This picture helps to illustrate the robust nature and importance of police effectiveness in giving orders to the civilians in the crowd. Note that when police effectiveness is at just 60%, the number of injured civilians does not increase appreciably, even at the highest levels of civilian desire to run from the enemy. It is only when effectiveness drops below 20%-30% that the number of civilians injured begins to increase with a greater civilian desire to flee. Note that the first split of the regression tree is when the police order effectiveness was 23%.

b. Gridded Experiment

The analysis shows that the effectiveness in police issuing orders to civilians is a dominating factor in determining the percentage of civilians injured at the end of the first hour of response. There are other questions that must be analyzed to gain an understanding of what is most important in emergency response.

- What role does communication degradation play in emergency response?
- Is there key terrain that the emergency response teams must ensure is secured to facilitate response?

The technique chosen to gain insight into those questions was to run a gridded experiment in which just three variables are changed: probability of communication, number of patrolmen at each location, and number of traffic police at each intersection. Probability of communication did not enter into the tree as a significant variable in the small FRLH experiment. In reality, communication is very important in emergency response, and one of the points highlighted first in most interagency AARs. The author was only able to vary communication over two levels in the small FRLH experiment. The gridded experiment resulted from varying communication and both other variables at five levels each.

Figure 27 shows the increase in R^2, with the number of splits in the regression tree, using data generated with the gridded model. Note that diminishing returns in R^2 occurs after the fifth split. The increase resulting from making five splits, versus four, is only 0.025, from 0.642 to 0.667. The result is a tree that has an R^2 of only 0.642, lower than we would like for predictive purposes; however, the purpose of this tree is not necessarily prediction, but gaining insight into the relationship of factors that the decision can control.

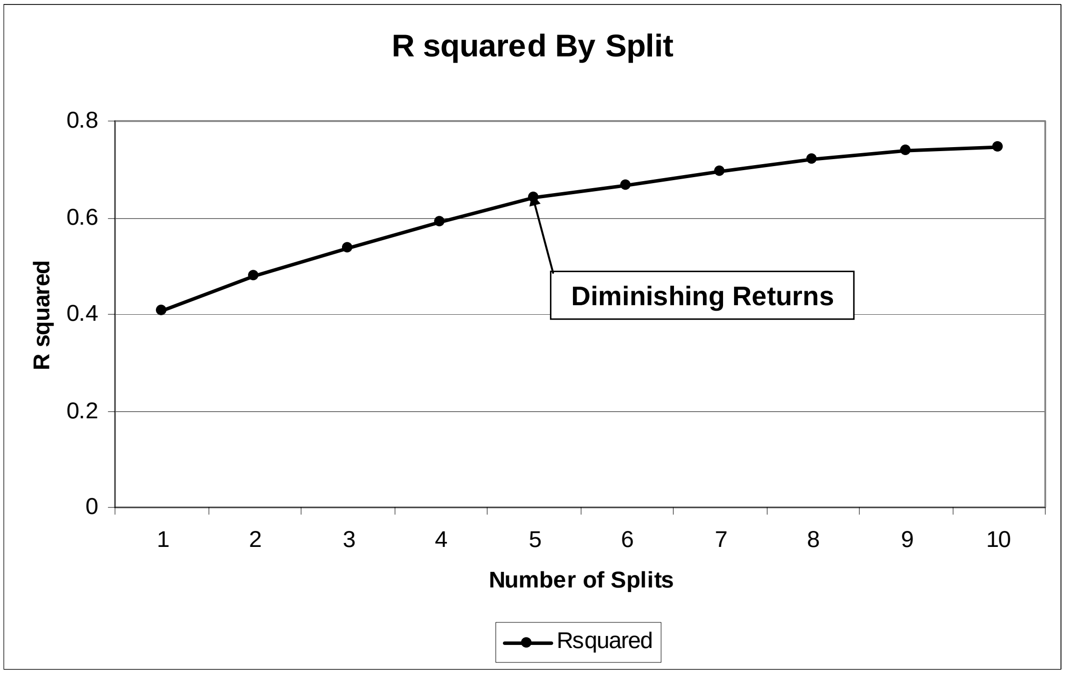


Figure 27. Analysis of R^2 by Regression Tree Split (Gridded Experiment, Response = Percentage of Injured Civilians)

Figure 28 is the regression tree developed in JMP, from the gridded data set, to help gain insight into the factors that influence the number of civilians that remain injured after the first hour. Within the tree, there is very little variability between the tree's best (approximately 91%) and worst case scenario (approximately 87%). This small amount of variability means that it may be difficult to fit a good model to the data.

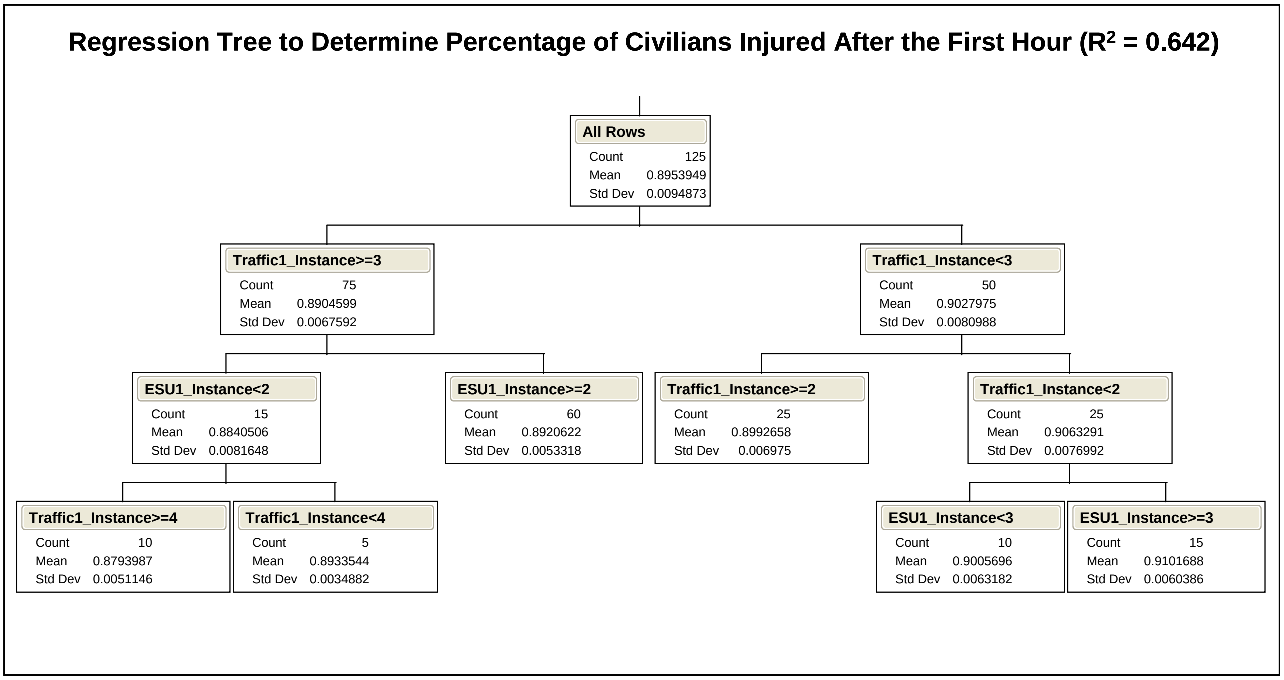


Figure 28. Regression Tree to Determine the Percentage of Civilians Injured After the First Hour (Gridded Experiment)

After making five splits, it is evident that communication does not seem to have significant importance in this model's emulation of first response. In fact, it is not until the tenth split (not shown) that the communication factor is included in the tree.

In retrospect, the lack of communication importance in this model vignette is not terribly surprising. Communication is meant to serve many functions in response, including, but not limited to: passing situational awareness in the form of information, sending information about enemy locations and dispositions, and providing direction in terms of orders.

As previously stated, in Section IV.A.5., the actions simulated in this research are the adaptation of work that occurs by standing operation procedure (SOP). SOPs are meant to minimize the need for communication and streamline operations; therefore, it is intuitive that in certain cases, communication factors may be dominated by others, such as location and numbers of forces, in the early stages of an emergency. However, a model could easily be adjusted to account for lack of SOPs, undisciplined following of SOPs, or SOPs that cannot be followed because of the situation. In these cases, analysis may reveal a higher level of importance for communication factors.

2. MOE 2. Percentage of Civilians at the Medical Triage Point After One Hour

Analysis of the second MOE follows the same pattern as the first. Figure 29 shows the increase in R^2 with the number of splits in the regression tree. Note that after the second split in the tree, the increase in R^2 is small. The increase resulting from making three splits, versus two, is only 0.042, from 0.791 to 0.833.

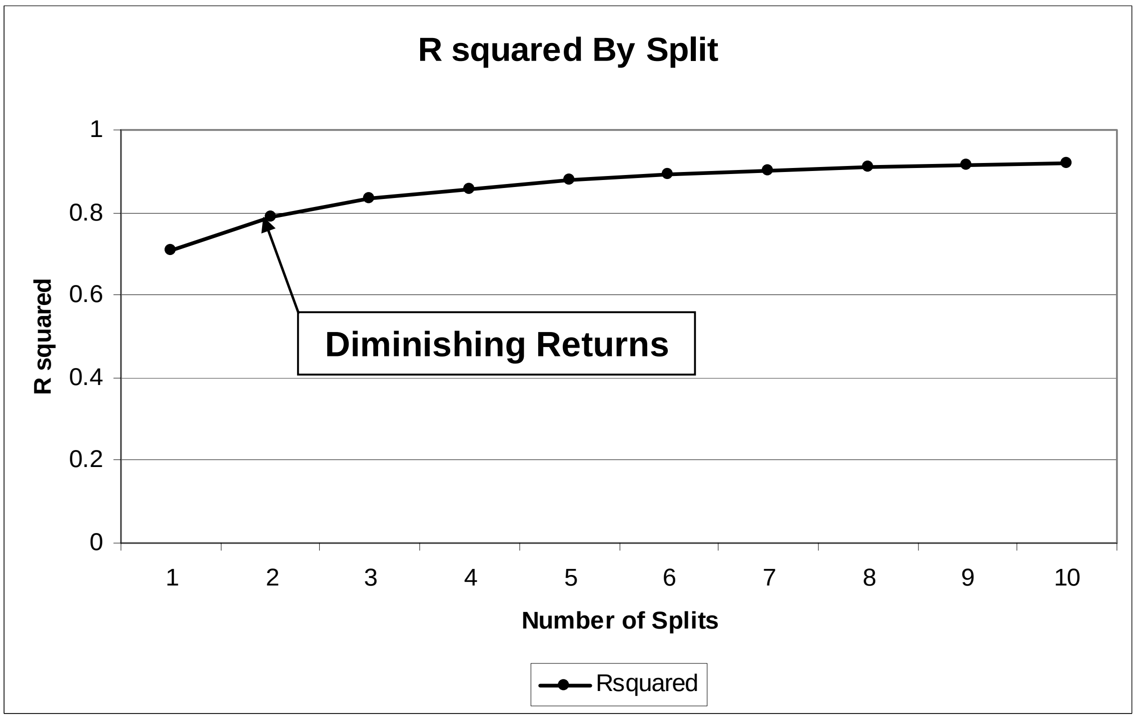


Figure 29. Analysis of R^2 by Regression Tree Split (Small FRLH Experiment, Response = Civilians at Triage Site)

Figure 30 shows the regression tree that results from splitting twice. Notice that police effectiveness in giving orders is the most important variable; in fact, it is the only variable involved in the tree for the first four splits.

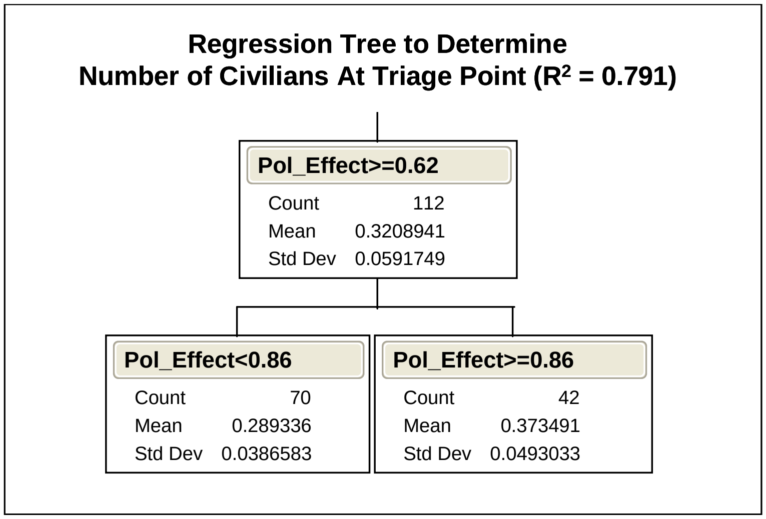


Figure 30. Regression Tree to Determine the Percentage of Civilians at the Medical Station (Small FRLH Experiment)

In the regression tree, police effectiveness has a dramatic impact on the percentage of civilians at the triage point, accounting for nearly 88% of the variance after four splits. Figure 31 shows multiple regression output that serves to verify the relationship of police effectiveness to percentage of civilians at the triage point. The step history indicates that police effectiveness is the first variable to enter the model, explaining about 77% of the variance. In the effect test, this variable seems to have a dramatically higher impact on the model than any other variable, shown by the F-test of 1,250, versus 25 and 20 for the next two highest variables.

Step History

Step	Parameter	Action	"Sig Prob"	Seq SS	RSquare	Cp	p
1	Pol_Effect	Entered	0.0000	1.733161	0.7659	96.602	2
2	Agitator_Marksmanship	Entered	0.0000	0.033254	0.7806	74.71	3
3	NUM_Ag_4	Entered	0.0000	0.028562	0.7932	56.189	4
4	Num_Civilians	Entered	0.0000	0.027852	0.8055	38.178	5
5	Num_Traffic_8	Entered	0.0046	0.012378	0.8110	31.284	6
6	Num_EMT_SJ	Entered	0.0111	0.009729	0.8153	26.295	7
7	Gunman_Vuln	Entered	0.0271	0.007238	0.8185	23.094	8
8	Num_Traffic_3	Entered	0.0313	0.006782	0.8215	20.221	9
9	Num_Fol_1	Entered	0.0329	0.006574	0.8244	17.498	10
10	Gunman_Marksmanship	Entered	0.0356	0.006297	0.8272	14.974	11
11	Num_Ag_2	Entered	0.0396	0.005964	0.8298	12.689	12
12	Num_ESU_3	Entered	0.0380	0.00599	0.8325	10.385	13

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Num_Ag_2	1	1	0.0061529	4.4632	0.0355
NUM_Ag_4	1	1	0.0280710	20.3620	<.0001
Num_EMT_SJ	1	1	0.0100637	7.3000	0.0073
Num_ESU_3	1	1	0.0059898	4.3449	0.0380
Num_Fol_1	1	1	0.0059475	4.3141	0.0387
Num_Traffic_3	1	1	0.0065470	4.7490	0.0302
Num_Traffic_8	1	1	0.0105662	7.6644	0.0060
Num_Civilians	1	1	0.0290635	21.0819	<.0001
Pol_Effect	1	1	1.7256186	1251.719	<.0001
Gunman_Vuln	1	1	0.0073219	5.3111	0.0219
Agitator_Marksmanship	1	1	0.0345315	25.0482	<.0001
Gunman_Marksmanship	1	1	0.0059173	4.2922	0.0392

Figure 31. Stepwise Regression Output from JMP, Response = Percentage of Civilians at Triage Point, Additive Model

Figure 32 shows the details of the multiple regression model developed. The original model is the one located on the left-hand side of the figure, an additive (main effect) model. Notice the Residual by Predicted Plot; there appears to be a quadratic relationship between the effectiveness of police orders and percentage of civilians at the triage point. After adding the quadratic term for police effectiveness (on the right-hand side of the figure), notice that the plots are much more well formed, with an R^2 of approximately 90%.

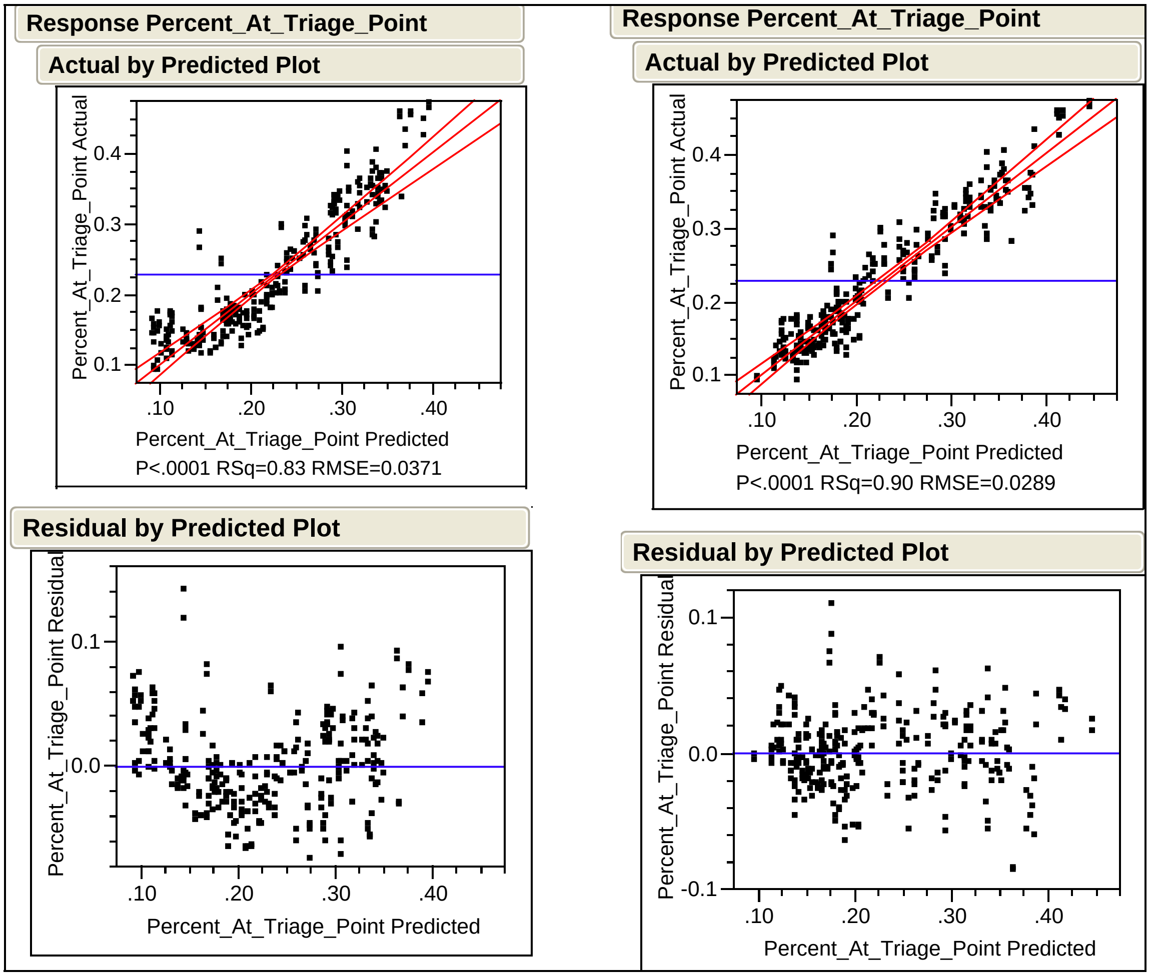


Figure 32. Stepwise Regression Plots

3. MOE 3. Neutralization of Enemy Gunman

a. Small FRLH

Analysis of the third MOE follows the same pattern as the first two. There is one difference in the generation of this MOE. There are several simulation runs in which the police force does not kill all of the gunmen. To account for this result, the author generated a binary variable. A value of 1 means at least one terrorist survives, while 0 means that all are dead. As the data are grouped and the means collected, the 0s and 1s are averaged to obtain the proportion of those 15 replications for which all of the gunmen are killed.

Figure 33 shows the increase in R^2 with the number of splits in the regression tree. Note that after the fourth split in the tree, there is no appreciable difference in R^2. The increase resulting from making four splits, versus five, is only 0.036, from 0.569 to 0.605.

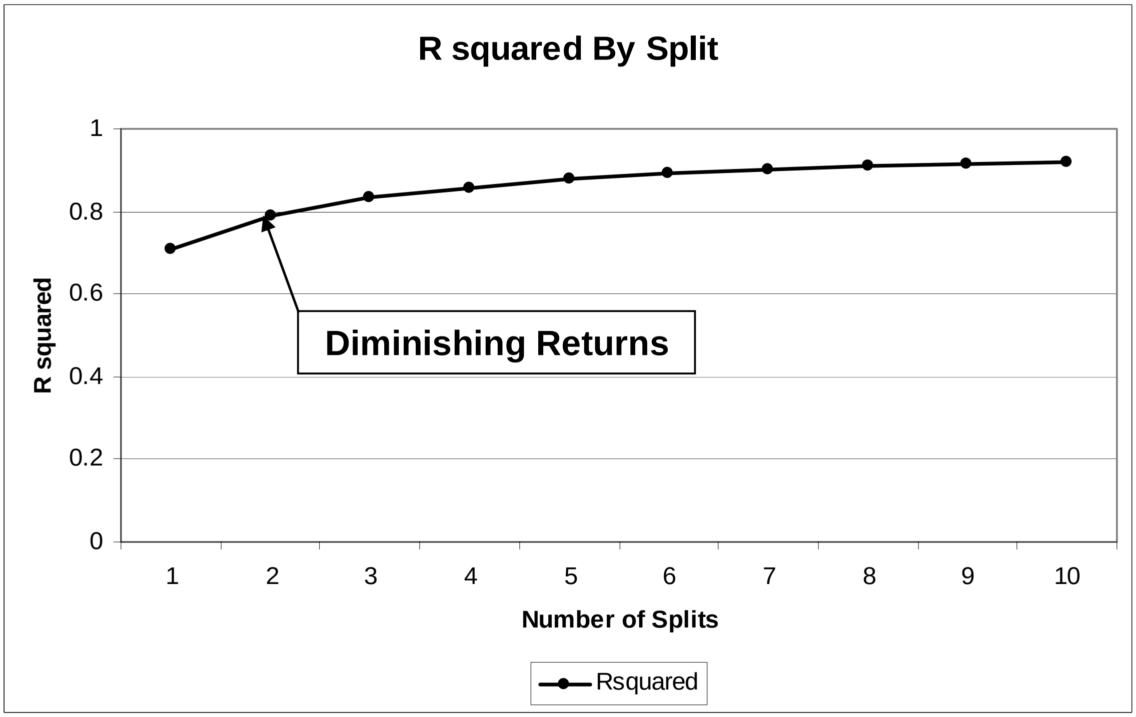


Figure 33. Analysis of R^2 by Regression Tree Split (Small FRLH Experiment, Response = Percentage of Gunmen Neutralizations)

Figure 34 shows the regression tree that results from splitting four times. Police effectiveness has importance in this model, but it does not show up as a factor until the third level, or fourth split. Of the four variables included in this model, only one is a factor that a decision maker on the first responder side can readily affect.

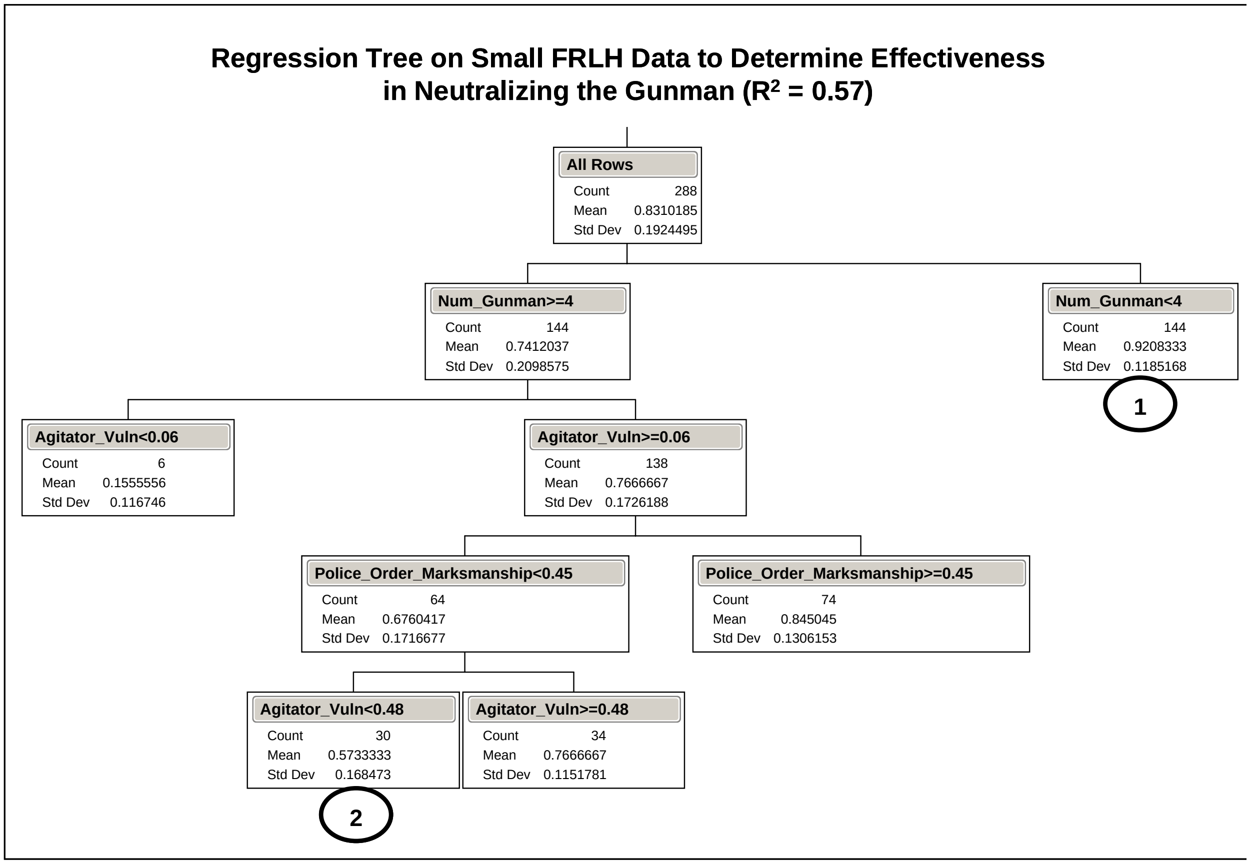


Figure 34. Regression Tree on Small FRLH Data to Determine Percentage of Gunmen Neutralized

Number 1 in Figure 34 shows the best case scenario: if there are less than four gunmen, we expect all of the gunmen to be neutralized approximately 90% of the time.

Number 2 in Figure 34 illustrates the worst case scenario. Below is the interpretation of this leaf in the decision tree. If

- there are more than four gunman, and
- agitator vulnerability is greater than 6%, and
- police marksmanship is less than 0.45, and
- if agitator vulnerability is less than 48%,

then you would expect all terrorist gunmen to be killed only about half the time.

Agitator vulnerability is involved in two of the four levels of this tree, highlighting a possible secondary effect that is intuitive. If the agitators are less vulnerable, they draw the attention of the first responders away from the gunmen.

b. Large FLRH Experiment

One of the strengths of MAS is the ability to “grow” data to analyze a given problem in greater and greater levels of detail. Analysis of the effectiveness in neutralizing the terrorist gunman is an example of this strength. The small FLRH experiment yielded several instances in which all of the terrorist gunmen were not killed. To ensure accurate insight is gained into the effectiveness of neutralizing the gunmen, more data can be “grown” using the principles of data farming. In this case, the large FRLH experiment resulted in a data set that was more than 10 times the size of the small experiment (45,360 rows versus 4,320 rows), enabling analysis at a finer level of detail.

Figure 35 shows the increase in R^2 with the number of splits in the regression tree. Diminishing returns in R^2 occurs after the fifth split. The increase resulting from making six splits, versus five, is only 0.047, from 0.534 to 0.581.

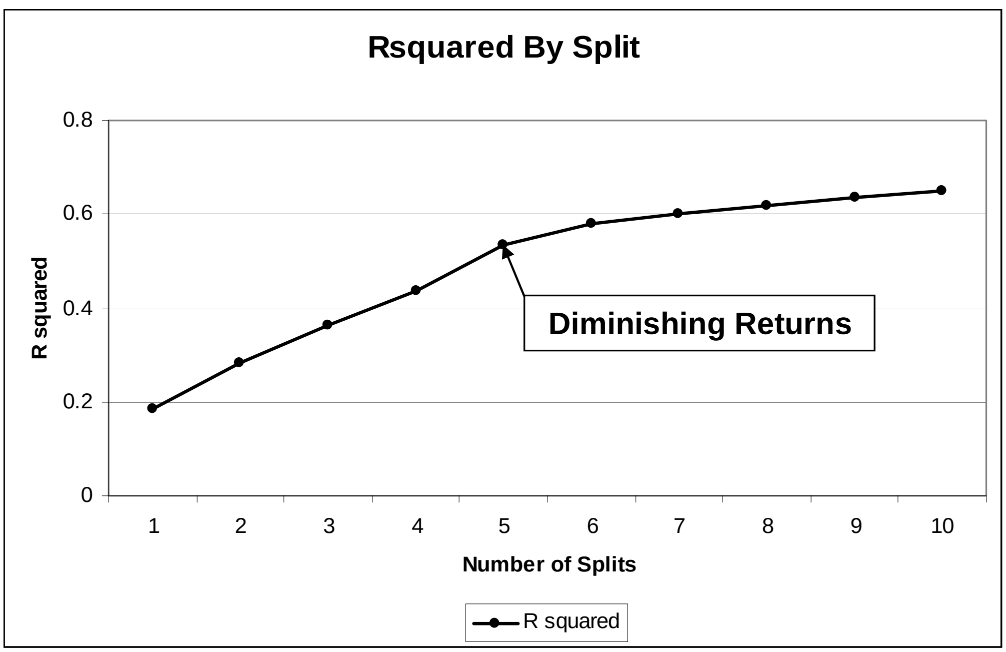


Figure 35. Analysis of R^2 by Regression Tree Split (Large FRLH Experiment, Response = Percentage of Gunman Neutralizations)

The regression trees resultant from modeling the large and the small FLRH have a key difference. In the large FRLH experiment, police order effectiveness is the most important factor; the single variable that explains the most variance (see Figure 36).

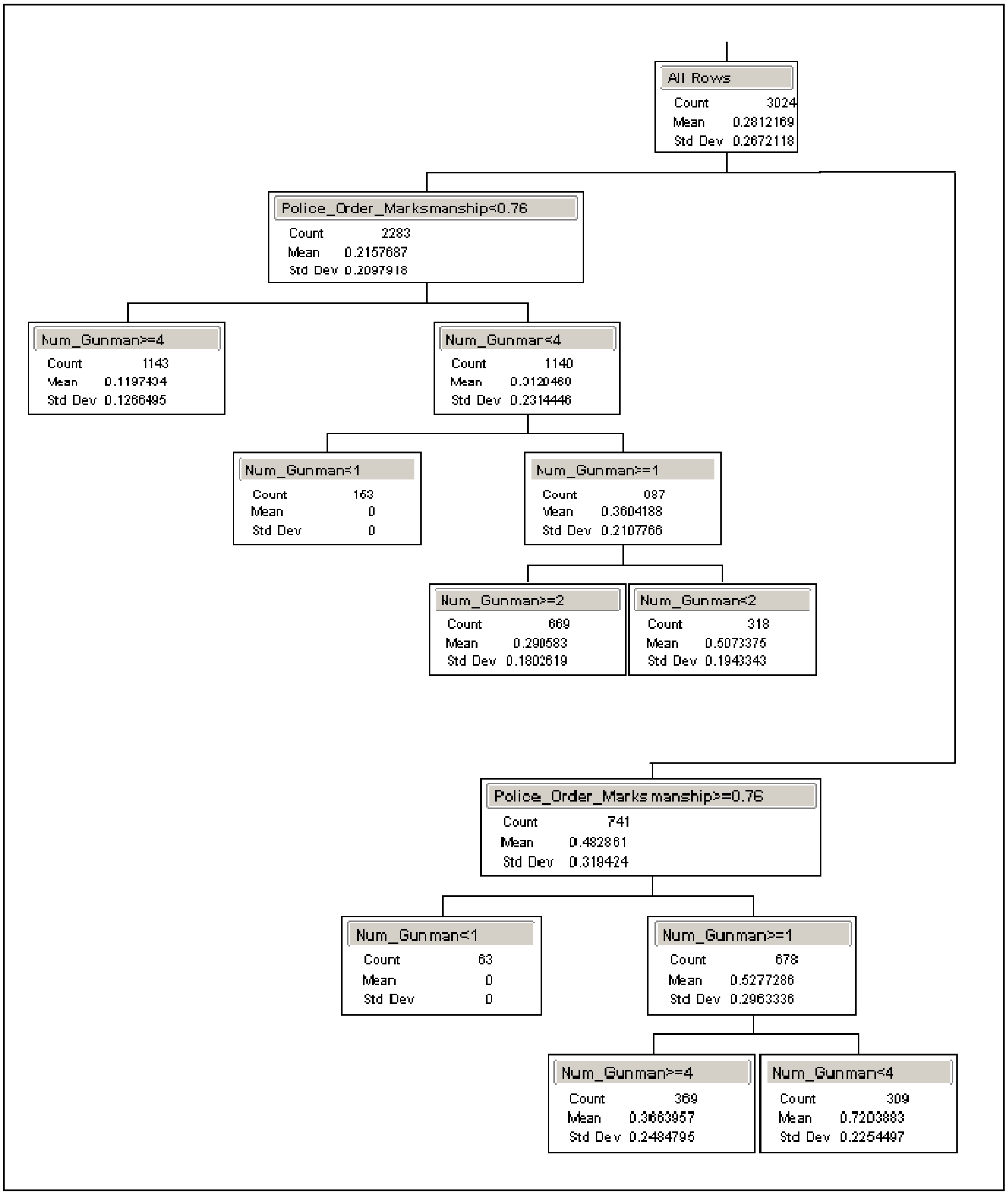


Figure 36. Regression Tree on Large FRLH Data to Determine Percentage of Gunmen Neutralized

As illustrated in Figure 36, only two factors (of a possible 38) are unique in the first six splits. See Figure 37 for a contour plot that highlights the relationship between police order effectiveness and the number of terrorist gunmen in determining if all the gunmen will be killed. The coarseness of the plot is explainable in part by the variables representing the 36 dimensions not captured on the axes. The picture contains an overlay of the splits made on the regression tree.

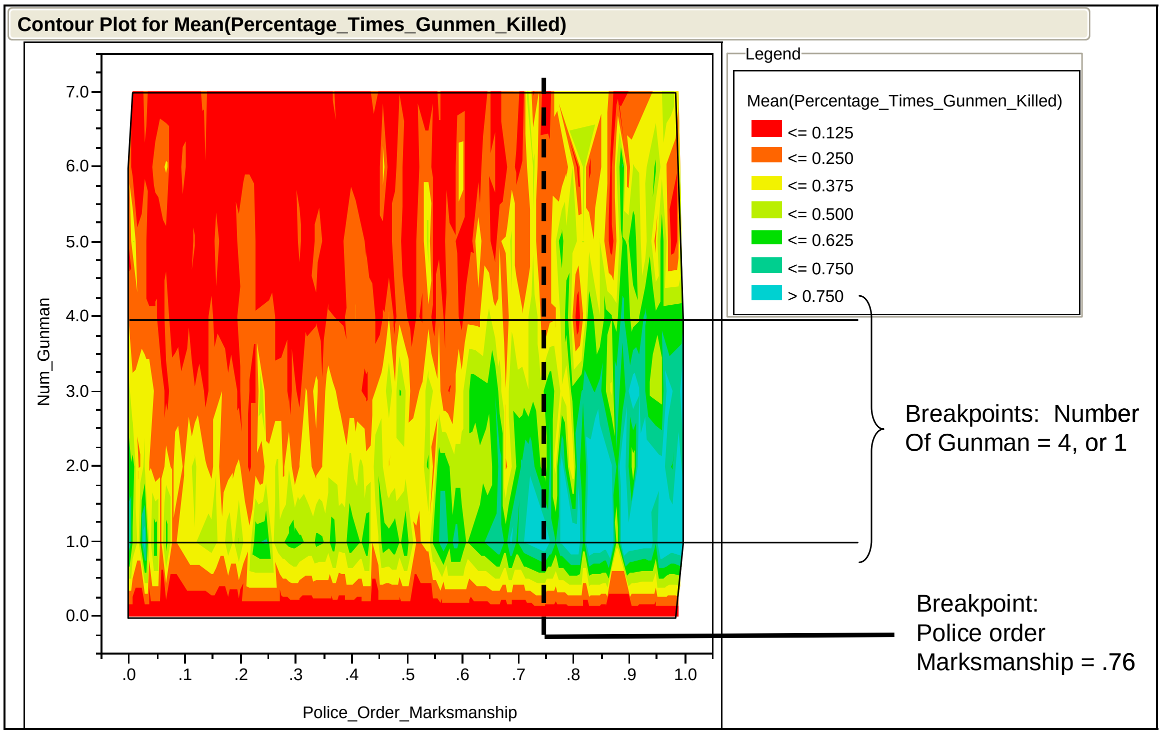


Figure 37. Relationship of Police Effectiveness in Giving Orders to the Number of Terrorist Gunmen in Determining Percentage of Times Gunmen Killed (Large FRLH Experiment) (best viewed in color)

The relationship between the number of gunmen in the simulation and the difficulty in killing them all is obvious. It may not be obvious why the effectiveness in the police officers' use of a paintball weapon impacts the survival of the gunmen. After viewing the simulation several times, a possible explanation lies in the police officers' focus. Simply put, they do not do two things at once very well. As the police order effectiveness increases, more civilians move to the triage points faster, resulting in the police having the ability to focus on killing the gunmen. Based on the settings given to the police, it is expected that, when more civilians are in the area, the police will be distracted by the additional civilians and not as responsive to the gunmen.

4. MOE 4. First Responders Killed or Wounded

Figure 38 shows the increase in R^2 with the number of splits in the regression tree. Note that after the third split in the tree, there is no appreciable difference in R^2. The increase resulting from making four splits, versus five, is only 0.035, from 0.687 to 0.722.

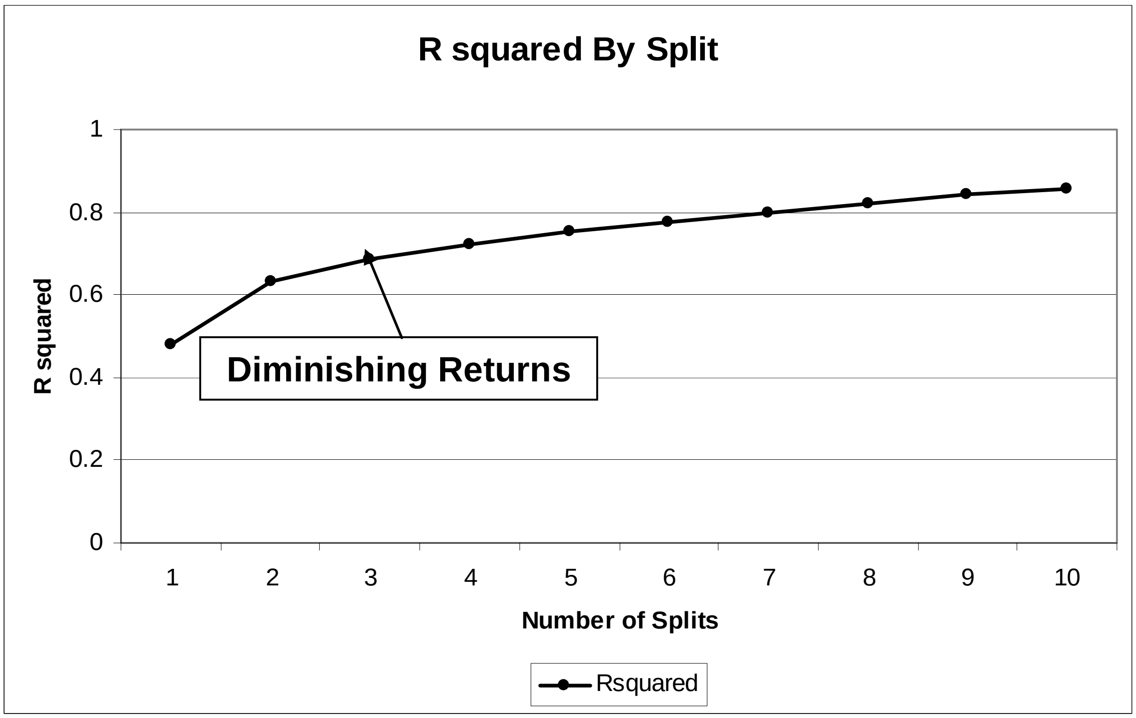


Figure 38. Analysis of R^2 by Regression Tree Split (Small FRLH Experiment, Response = Proportion of First Responders Killed or Injured)

Figure 39 shows the regression tree that results from splitting three times. Police effectiveness is again the most important factor in predicting our response variable, the proportion of first responders killed or injured in the first hour. Figure 40 shows a check done with linear regression to ensure that similar variables are included with an additive multiple regression model (without interactions). Fortunately, both methods yield similar results, both in variable selection and in R^2; therefore, we can be confident that we are truly capturing the most important variables in the scenario.

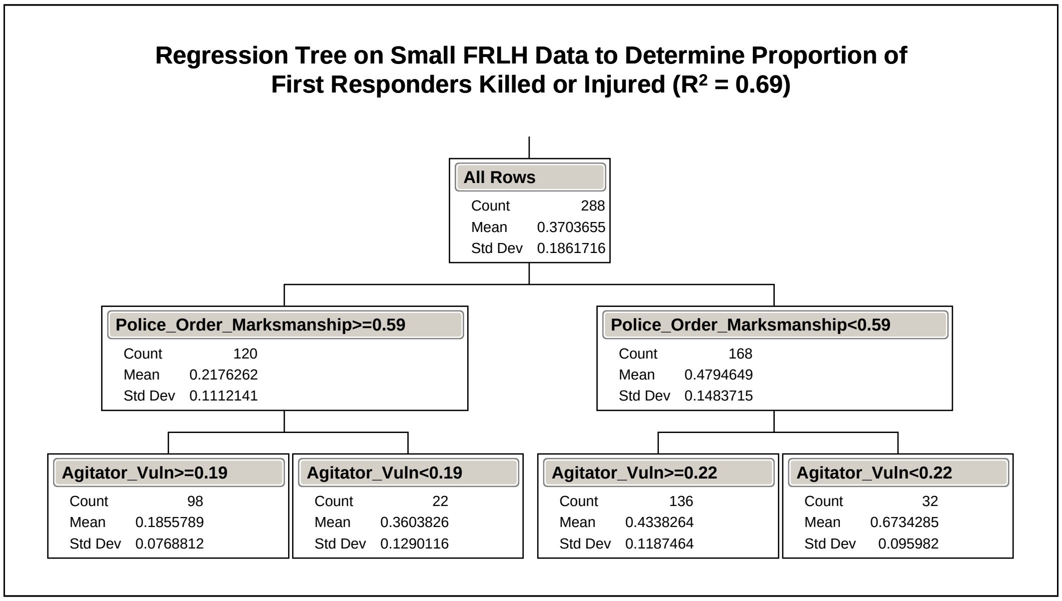
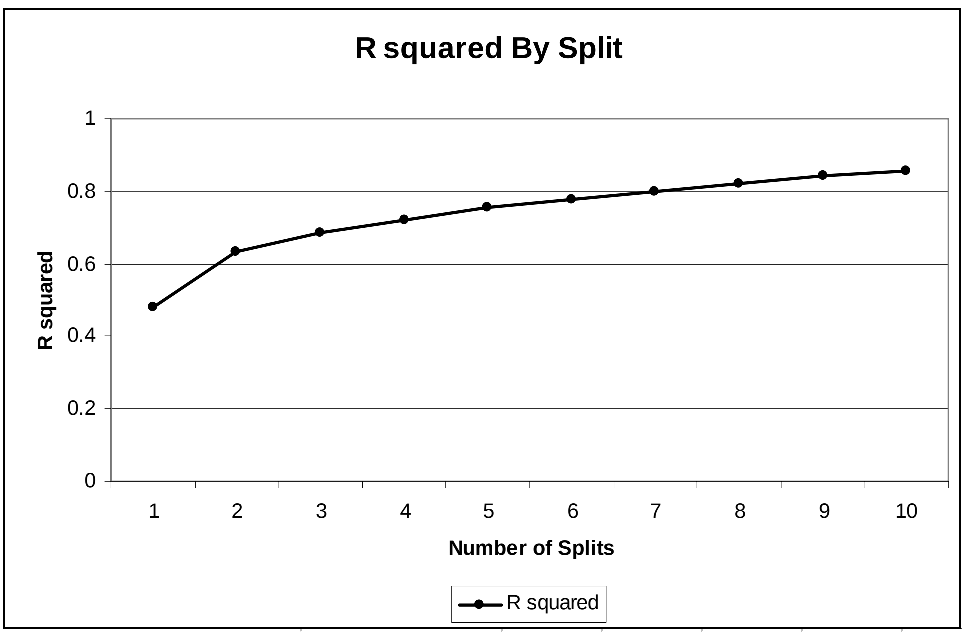


Figure 39. Regression Tree on Small FRLH Data to Determine Proportion of First Responders Killed or Injured



Step History

Step	Parameter	Action	"Sig Prob"	Seq SS	RSquare	Cp	p
1	Police_Order_Marksmanship	Entered	0.0000	4.707798	0.4733	385.61	2
2	Agitator_Vuln	Entered	0.0000	0.931277	0.5669	268.59	3
3	Agitator_Marksmanship	Entered	0.0000	0.471817	0.6143	210.3	4
4	Num_Gunman	Entered	0.0000	0.338301	0.6483	169.06	5
5	Num_Ag_2	Entered	0.0000	0.206709	0.6691	144.65	6
6	Num_EMT_SJ	Entered	0.0003	0.153511	0.6845	127.03	7

Figure 40. Results of Multiple Regression (Stepwise) Variable Selection (Small FRLH Experiment, Response = Proportion of First Responders Killed or Injured)

It is interesting that police marksmanship, or effectiveness in giving orders to civilians, has a dramatic impact on the proportion of first responders that are killed or injured. This type of "marksmanship" is associated with a paintball weapon that should not directly affect first responders. Further inspection of the scenario and the model will determine whether police order marksmanship has its effect directly, or through a synergistic effect or emergent behavior caused in other agents.

Figure 41 illustrates the relationship between vulnerability of terrorist agitators and effectiveness of police in using their paintball "orders" weapon. The data points are included in this plot to give the reader an idea of the data filling nature of Hernandez's FRLH design.

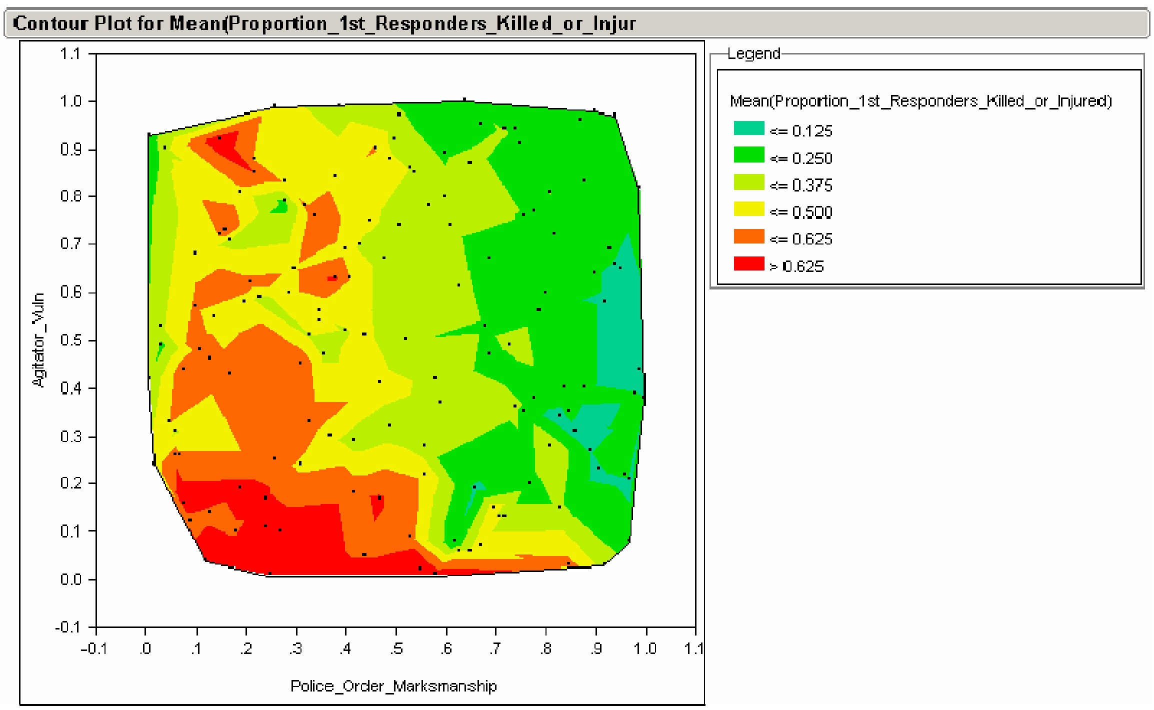


Figure 41. Relationship of Police Effectiveness in Giving Orders to Terrorist Agitator Vulnerability in Determining Proportion of First Responders Killed or Injured (Small FRLH Experiment)

The relationship depicted in Figure 41 is as one would expect, if the weapon addressed with police marksmanship is a lethal weapon. Because it is a paintball weapon, it is important to check the model settings and ensure that there is no artifact in the simulation that is causing the weapon to have a capability that the weapon should not have.

This chapter was an analysis of the data that resulted from execution of the simulation model developed in accordance with steps 9 and 10 of the methodology established in Figure 5 of this work, and run using efficient experimental design, steps 11 and 12. Given more time, much more analysis could be accomplished with this data. The data analysis began with gaining quick insight into the data, using a small FRLH design. Areas of particular interest were brought into further focus using two more detailed approaches, a gridded design, and a larger, more space filling Latin Hypercube design. The final chapter of this research provides the conclusions gained from the development of the first response simulation methodology and analysis of the simulation data. In addition to the conclusions of this study, Chapter VII includes recommendations for future study.

VII. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

This chapter summarizes the contributions of this research, describing both general methodological contributions and specific findings that relate to the established research questions. Following the discussion of conclusions, the author provides recommendations to government agencies for planning and coordinating emergency first response. Recommendations for future study comprise the final section of this research, outlining ways in which this work can be carried forward.

A. CONCLUSIONS AND CONTRIBUTIONS

1. Methodology Contributions

a. Organizational Learning Methodology

Organizational learning is a process by which an organization deliberately expands its knowledge base for a certain purpose. The methodology proposed in Figure 2 of Chapter I illustrates how to use low resolution simulation in conjunction with high resolution simulation to facilitate the organizational learning process during preparation for a TOPOFF exercise. Application of this methodology can certainly result in more effective planning, a more focused exercise, and a better-trained response force. In addition, application of this methodology could result in more efficient use of sparse resources, such as training dollars and manpower.

b. Emergency First Response MAS Methodology

Simulation of emergency first response provides decision makers with a tool that provides insights that cannot practically be gained through other means. The ability to analyze tens of thousands of different situations and variable combinations provides the analyst with the ability to gain a much more thorough knowledge of a problem's response surface than can be provided by subject matter expertise or point estimates, gained through high resolution simulation. The methodology presented in Figure 6 of Chapter III shows a step-by-step process that an analyst can follow to use a low resolution simulation to credibly analyze emergency first response to a crisis situation.

c. Experimental Design Methodology

Efficient experimental design is the bridge that enables the MAS to be analyzed in several dimensions, fully leveraging the power of modern computers. The experimental design methodology developed in Chapter V provides the analyst with a mechanism to take a broad approach to initial analysis, using Hernandez's FRLH designs. The analyst then narrows the focus on areas of interest, using a space filling NOLH design, such as those developed by Cioppa. Finally, to isolate the effects of a small number of variables, the analyst can utilize a gridded design.

2. Analytical Conclusions

The analytical results here demonstrate a proof of concept. It is possible to gain useful insight through the utilization of a low resolution model, such as a MAS. Although it is possible to provide decision support analysis, the findings in this research should not be directly applied to the TOPOFF process or to Baltimore first responders. To provide analysis that is relevant to a given agency, it is imperative that accurate local force structure and SOPs be obtained. In addition, local subject matter experts (SMEs) should be involved in model verification. When these steps are taken, it is possible that insights such as those described in Chapter 6 can be relevant to first response organizations.

Overall, the most important factor in determining the effectiveness of first response forces is the effectiveness with which the police forces are able to calm the civilians and direct them to the triage points. Due to the ROE used for the police in this simulation, they fixate on the civilian they are assisting, until that civilian receives the help he or she needs. If the police are effective, they can then move on to other priorities of work, such as addressing an injured unit member or terrorist threat. If the police are not effective, they do not disengage and execute another mission.

a. What is the Most Appropriate Mix of Response Forces?

This analysis provided insight into the determination of response force mix by focusing on two fundamental first response MOEs:

- Percentage of civilians not treated in the first hour
- Percentage of civilians relieved of panic in the first hour

Although not able to determine a true recommended mix of police forces to medics to firemen, the analysis showed that the number of responders is not as important as their effectiveness.

(1) Number of Civilians Injured After the First Hour. This MOE measures the effectiveness of the first responders in addressing the civilians' physical needs, i.e., first aid and medical stabilization. Effective police interpersonal relationship skills with the crowd is the most important factor in determining how many civilians are injured after the "Golden Hour," the first hour after an incident. At medium and high levels of police effectiveness, only a few injured civilians are able to depart the first response area of influence without being given first aid by a policeman or treated by a medic. It is only at very low levels of effectiveness that the police become "overwhelmed" by the number of civilians in the area of the bomb blast and are not as effective.

(2) Percentage of Panic-Relieved Civilians After the First Hour. This MOE measures the first response force's ability to address the civilians' psychological needs, i.e., the ability to calm the crowd and restore order. Police effectiveness in maintaining crowd control is again the most important factor in addressing the needs of civilians, and clearly dominates all of the other 36 factors considered in the analysis.

b. *What is the Impact of Communication Effectiveness in Emergency First Response to a VBIED in Baltimore's Inner Harbor?*

Communication effectiveness plays a key role in the ability of command and control elements to relay information vertically and laterally to increase response force situational awareness in the response area. This simulation analyzes possible *physical* characteristics of communication, i.e., effectiveness of a given piece of equipment. This model does *not* attempt to simulate the human dimension of communication, such as measuring the equivalence of the message sent versus the message received.

(1) Neutralization of Terrorist Gunmen. In this simulation, a key feature is the passing of information from the first responders to an incident command cell. The incident command cell then processes and laterally passes the information to other command cell members; the consolidated information is disseminated to unit members. One such piece of information is the location of terrorist gunmen. The analysis showed that communication was not a key factor in the neutralization of the enemy gunmen; rather, police effectiveness in giving orders to civilians and the number of gunmen were the dominant factors.

A possible explanation exists for the counterintuitive importance of police orders. Importance of orders may lie in the ROE. In this simulation, police have a higher desire to help the civilians than kill the enemy. As such, with decreased police effectiveness, the civilians are not helped as quickly. The police, engaged in trying to assist the civilians with decreased effectiveness, do not disengage from the civilians in order to address the threat of gunmen.

The lack of importance of communication may result from the procedural nature of first response. Effective first response involves effective execution of SOPs. Communication, while important to maintain situational awareness, may not be a key factor in first response. Agencies know what to do when they arrive on scene, most likely have trained on it, and are prepared to execute in accordance with local SOPs. Communication becomes of paramount importance in the execution of the follow-on mission, as police, fire, and medical forces arrive from outside the crisis area (not modeled in this simulation). The incident command post must dispatch these units to the appropriate area, requiring communication and situational awareness. This simulation ends before these additional follow-on forces arrive, a possible reason why communication does not appear as a relevant factor in this analysis.

(2) Proportion of First Responders Killed or Wounded. The proportion of first responders killed or injured relates to the importance of communication in a similar manner to the neutralization of the terrorist gunmen, but adds an additional dimension. Police must neutralize the lethal threat of the gunmen, or incur additional casualties. All first responders must be able to communicate their injury status to unit members to be able to receive medical attention.

Communication does not appear to be a relevant factor in determining the proportion of first responders killed or injured. Rather, the most important factor is police effectiveness in addressing civilian needs. As suggested in section VI.B.1.b, this may have been the result of modeling SOPs. Again, a model could easily be adjusted to account for lack of SOPs, undisciplined following of SOPs, or SOPs that cannot be followed because of the situation. In these cases, analysis may reveal a higher level of importance for communication factors.

B. RECOMMENDATIONS FOR EMERGENCY PREPAREDNESS

Simulation is a valuable tool that first response agencies could use to facilitate emergency preparedness in two ways:

- Training of leaders and staff
- Exercise planning

1. Training of Leaders and Staff

Emergency response organizations at virtually all levels should use simulation as part of their training program for leaders and staff. Planning, executing, and analyzing a simulation provides a forum that helps leaders and staff better understand local SOPs. Executing a credible simulation requires the simulation to emulate reality. To prepare the simulation, the modeler must thoroughly understand what the SOP says, but also what it means: the effect meant to be achieved by a certain directive. During the execution of the simulation, the training audience may see emergent behavior by agents that causes them to question and improve certain facets of the SOP. During the analysis of the data generated by the simulation, the leaders and staff may encounter surprises in the data that also causes the reexamination of portions of the SOP.

2. Exercise Planning

Planners can make large-scale exercises more effective training tools through the use of the organizational learning process that incorporates the MAS modeling methodology established by this research. Through the development and execution of simulations, leaders and staff develop an understanding of the given problem that is simply not gained through less structured brainstorming and planning sessions.

C. RECOMMENDATIONS FOR FUTURE STUDY

Analysis of a given problem can result in the development of as many or more questions than it solves. This analysis is no exception. The author used a very specific set of assumptions to complete this simulation. The simulation and the subsequent analysis can be considered one data point. Many more data points are needed to better understand the full capability represented in this research.

This research included a cursory qualitative comparison of the MAS developed to a well-established, high resolution model, EPiCS. A future project could be the development of a methodology to quantitatively assess the calibration of this model to EPiCS. The work could then generalize the comparison methodology to include the comparison of other MAS simulations to appropriate high resolution simulations.

In addition to being calibrated by another model, this model can be calibrated using actual events. With the assistance of the DHS or the City of New London, this model could be populated with actual force structure and SOPs associated with the response forces for TOPOFF 3. The model could then be run and analyzed to determine how close it came to replicating the actual events of TOPOFF 3 in New London.

Typically in crisis situations, the affected civilians react in different ways. Future work could involve the representation of civilians that assist emergency responders in the accomplishment of their mission. In addition, it is possible to model civilians that work against first response forces, e.g., by looting or even attacking first responders. Interaction with helpful civilians or antagonistic civilians may sway a neutral civilian to one side or the other. The author led preliminary work in this area during the 12th Project Albert International Workshop (PAIW), held in Boppard, Germany. See Appendix D (PAIW – 12 Findings) for details.

This simulation involved the execution of one set of first response and enemy courses of action. Follow-on work could examine the execution of different courses of action for both first response and terrorists. It would be interesting to note first response courses of action that are most robust against a variety of terrorist courses of action.

Another possible project that could spring from this work is analyzing the usefulness of separate vignettes from the model in answering research questions. It is possible that some research questions do not require the aggregation of all agents and agencies. Disaggregation of the model could result in much lower processing times for simulation runs, meaning a quicker turn around of data for analysis. While losing the synergistic effects of including all agencies in the model, disaggregation may be appropriate in some circumstances.

The Pythagoras scenario files, Excel modeling files, and all cited electronic references are available by contacting MAJ Jonathan Roginski, United States Military Academy, Department of Mathematical Sciences, West Point, New York, or by e-mail at jonathan.roginski@us.army.mil.

APPENDIX A – MODEL IMPLEMENTATION

This appendix provides detailed information about the numbers the author used in this research. Included are details about how distances were measured for the scale of the simulation, terrain settings, weapon characteristics, and side affiliations of agent classes. The purpose of this appendix is to make this simulation as transparent as possible, to reveal what is going on "under the hood."

A. OVERALL MODEL CONFIGURATION

1. Scaling

Figure 42 is a terrain snapshot of the Celebrate Baltimore area, taken using Google Earth, centered on the Amphitheater in Baltimore's Inner Harbor.

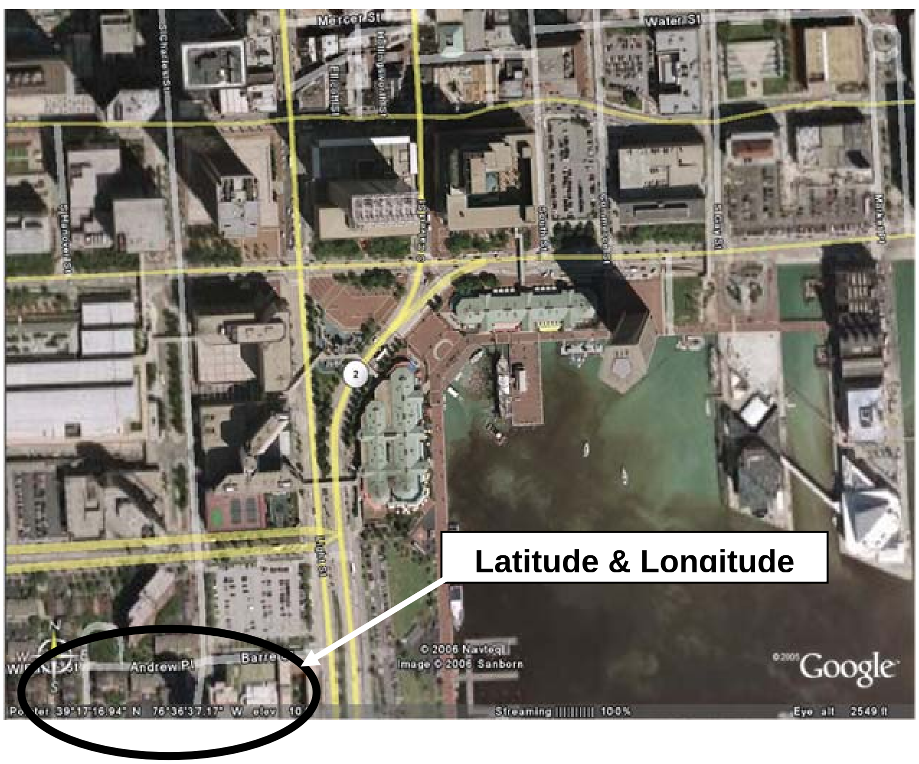


Figure 42: Terrain Snapshot of Celebrate Baltimore Area[66]

[66]Image downloaded from the World Wide Web using Google Earth on 12 April 2006.

To measure the actual size of this representation, the author used the latitude and longitude measurements at the four corners of the picture and entered them into a latitude/longitude to feet distance converter found at: http://www.epa.gov/athens/learn2model/part-two/onsite/ll-dms.htm.

See Figure 43 for the width of the above snapshot and Figure 44 for the height.

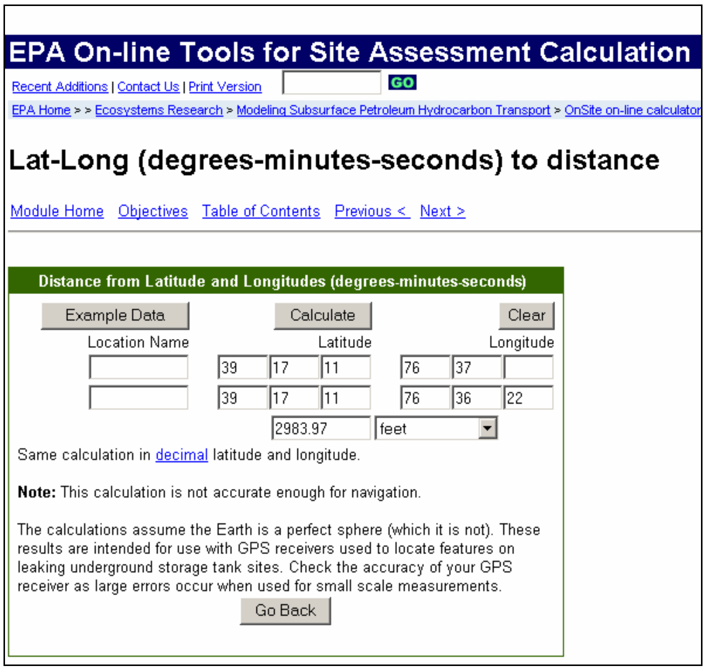


Figure 43: Calculation of Terrain Box Width

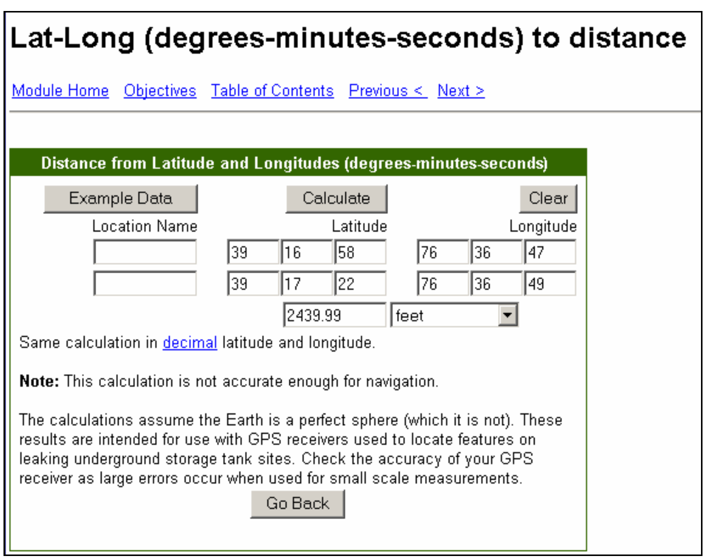


Figure 44: Calculation of Terrain Box Height

The goal of achieving a 2,000-foot by 2,000-foot square box would be achieved by making a smaller box that is approximately 67% of the current box's width and approximately 80% of its height.

2. Terrain

Figure 45 illustrates the selection concealment factor and selection of ceiling height. The modeler decides on a concealment factor that guards against detection in the three sensing spectra. These factors are located in the GUI on a sliding scale, from 0.0 to 1.0 (least visible to most visible). Movement and protection factor are located below concealment, and are scaled in the same manner as concealment. A movement factor of 0.0 means that an agent cannot move within this terrain feature, while a factor of 1.0 results in unencumbered movement. A protection factor of 1.0 results in total protection, while 0.0 results in no protection.

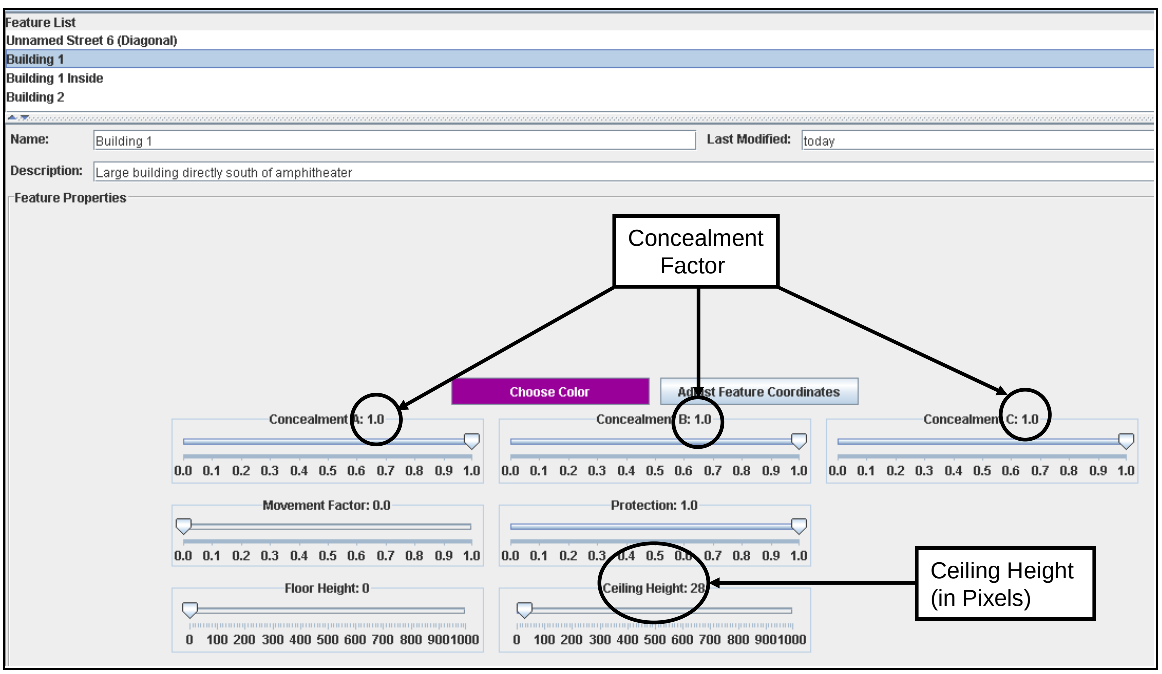


Figure 45: Instantiating Terrain Factors

Figure 46 shows the Pythagoras representation of the terrain located in Figure 42.

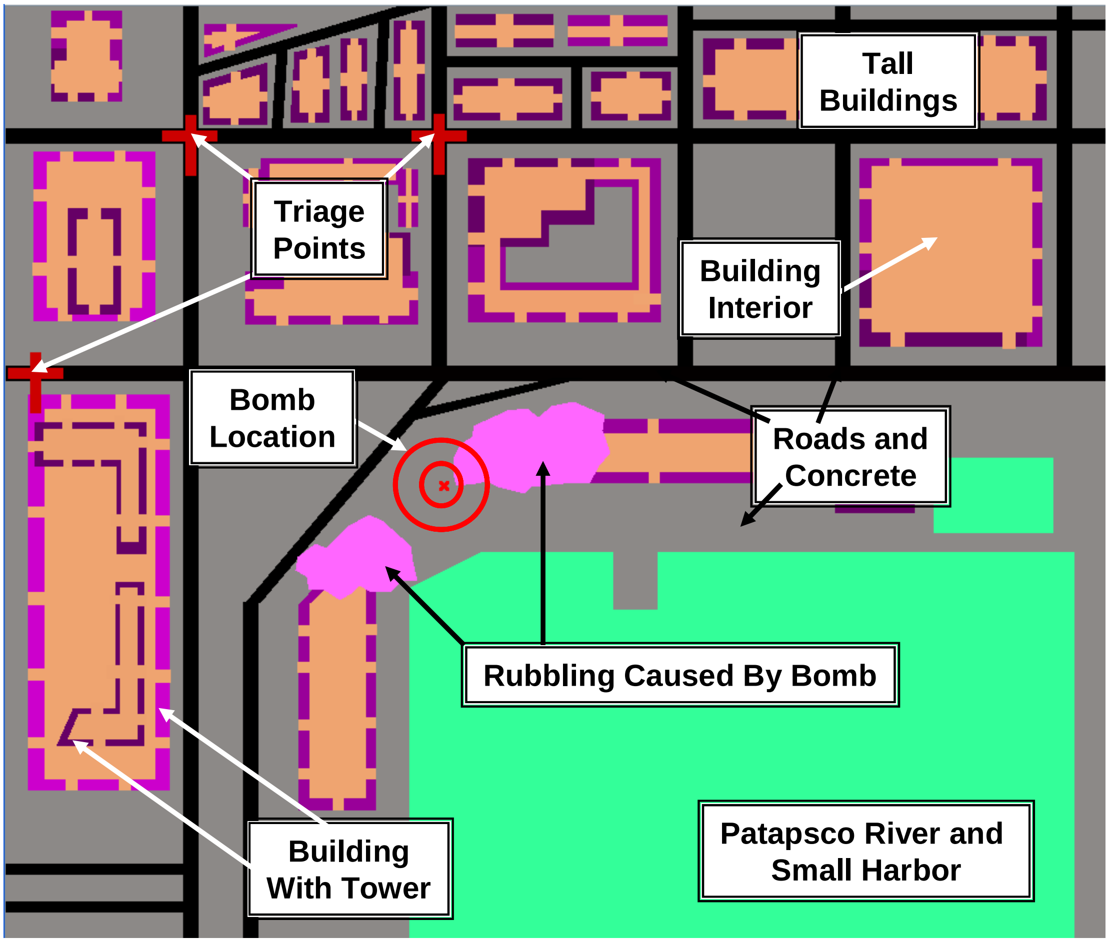


Figure 46. Pythagoras Representation of Celebrate Baltimore Area

3. Weapons

Figures 47-49 show the weapon settings used in this simulation. In Figure 47, fire rate per minute and engagement range each have columns that represent the actual scale values and their corresponding values as scaled for this Pythagoras simulation. The workbook used to track weapon characteristics was adapted from research completed by Major Michael Babilot, USMC.[67]

[67] Michael Babilot, "Comparison of a Distributed Operations Force to a Traditional Force in Urban Combat," Masters Thesis, Naval Postgraduate School, Monterey, CA, September 2005.

General Weapon Characteristics												
	Type	Effect-iveness	FireRate per Min	Pythag FireRate	Max Engage Range(m)	Pythag Max Range	Basic load	Random Damage Degree*	Suppress Duration	WpnTGT	Direct Fire
AMSAA Data	M4	1	15	1.00	336	550	300	1	0	E	Y
	M9	1	5	0.33	50	82	45	0.25	0	E	Y
	AK47	1	100	6.67	300	492	300	1	0	E	Y
	Agitator	1	7.5	0.50	31	50	500	0.8	0	E, N	Y
	Bomb (Carleton)	1	15	1.00	2	3	1	0.5	0	F, E, N	N
	Bomb (Cookie Cutter)	1	15	1.00	2	3	1	0.75	0	F, E, N	N
	Medical Kit	0.75	3	0.20	2	2	20	0.2	0	U, F, N	Y
	Orders - From Firemen	1	7.5	0.50	31	50	500	0	0	F, N	Y
	Orders - From Medics	1	7.5	0.50	31	50	500	0	0	F, N	Y
	Orders - From Police	1	7.5	0.50	31	50	500	0	0	F, N	Y

Figure 47. General Weapon Characteristics

Figure 48 shows weapon paintball characteristics assigned by the author for this scenario.

Paintball Characteristics						
	Delta			Delta		
Type	Red	Green	Blue	Alpha	Beta	Gamma
M4						
M9						
AK47						
Agitator				10		
Bomb (Carleton)				20		
Bomb (Cookie Cutter)				20		
Medical Kit				-10		
Orders - From Firemen				-10		
Orders - From Medics				-10		
Orders - From Police				-10		

Figure 48. Paintball Weapon Characteristics

Figure 49 represents probability of hit data entered for the weapons in the model.

Probability of Hit														
			RANGE											
		Pyth*	2	5	41	82	164	328	492	656	820	984	1148	1312
	Type	Real**	**1**	**2**	**21**	**41**	**82**	**164**	**246**	**328**	**410**	**492**	**574**	**656**
AMSAA Data	M4		1.00	1.00	0.75	0.63	0.47	0.30	0.22	0.15	0.11	0.00	0.00	0.00
	M9		1.00	1.00	0.50	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	AK47		1.00	1.00	0.75	0.63	0.46	0.30	0.21	0.14	0.10	0.00	0.00	0.00
	Agitator	p	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Bomb (Carleton)	H						See probability of kill data						
	Bomb (Cookie Cutter)	i						See probability of kill data						
	Medical Kit	t	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orders - From Firemen		1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	Orders - From Medics		1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	Orders - From Police		1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

*Units of measurement for Pythagoras distances are pixels
**Units of measurment for Real distances are feet

Figure 49. Probability of Hit Data

Figure 50 shows the probabilities of kill (for lethal weapons) or probabilities of restoration (restorative weapon), given that targets are hit in a certain engagement. This is different than SSPK. SSPK is calculated for a certain weapon, at a range by multiplying the numbers given in Figures 49 and

50. If the range is not shown in the figures, use linear interpolation between the next highest and next lowest number.

Probability of Kill Given Hit														
			RANGE											
		Pyth*	1	5	41	82	164	328	492	656	820	984	1148	1312
	Type	**Real****	**1**	**3**	**21**	**41**	**82**	**164**	**246**	**328**	**410**	**492**	**574**	**656**
AMSAA Data	M4		1.00	0.90	0.52	0.52	0.51	0.49	0.46	0.44	0.42	0.40	0.36	0.32
	M9		1.00	0.95	0.71	0.50	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	AK47	Pkill	1.00	0.90	0.58	0.58	0.57	0.55	0.54	0.53	0.53	0.53	0.49	0.47
	Agitator		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bomb (Carleton)		1.00	1.00	0.98	0.93	0.74	0.30	0.07	0.01	0.00	0.00	0.00	0.00
	Bomb (Cookie Cutter)		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.00	0.00
	Medical Kit		0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orders - From Firemen		1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orders - From Medics		1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orders - From Police		1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

*Units of measurement for Pythagoras distances are pixels
**Units of measurment for Real distances are feet

Figure 50. Probability of Kill, Given Hit Data

4. Agent Side Property

Figures 51 and 52 provide detailed information about the side affiliations of each agent class instantiated in this simulation, using a spreadsheet tool developed by Northrup Grumman.

				Unit				Friendly				Enemy			
Agent Name	Red	Green	Blue	Color Radius	Use Red	Use Green	Use Blue	Color Radius	Use Red	Use Green	Use Blue	Color Radius	Use Red	Use Green	Use Blue
Agitator (Start)	155	150	0	100	1	0	0	50	1	0	0	150	1	0	0
Agitator Shot 1	165	120	0	100	1	0	0	50	1	0	0	150	1	0	0
Agitator Shot 2	175	90	0	100	1	0	0	50	1	0	0	150	1	0	0
Agitator Shot 3	185	60	0	100	1	0	0	50	1	0	0	150	1	0	0
Agitator Shot 4	195	30	0	100	1	0	0	50	1	0	0	150	1	0	0
Agitator Shot 5	205	0	0	100	1	0	0	50	1	0	0	150	1	0	0
Civilians	0	200	0	0	1	1	1	150	0	1	0	200	1	0	0
Hospital	0	220	205	0	0	0	1	200	0	1	0	200	1	0	0
Inner Harbor	0	220	215	0	0	0	1	160	0	1	0	200	1	0	0
Central PD	0	220	225	0	0	0	1	160	0	1	0	200	1	0	0
SWAT - A1	0	220	235	0	0	0	1	160	0	1	0	200	1	0	0
Fire	0	220	245	0	0	0	1	160	0	1	0	200	1	0	0
Traffic	0	220	235	0	0	0	1	160	0	1	0	200	1	0	0
Terrorist Gunman	250	0	0	0	0	0	1	50	1	0	0	150	1	0	0

Please put only binary values (0 = No, 1 = Yes)

Please put only binary values (0 = No, 1 = Yes)

Please put only binary values (0 = No, 1 = Yes)

Figure 51. Color Definitions of Each Agent Class

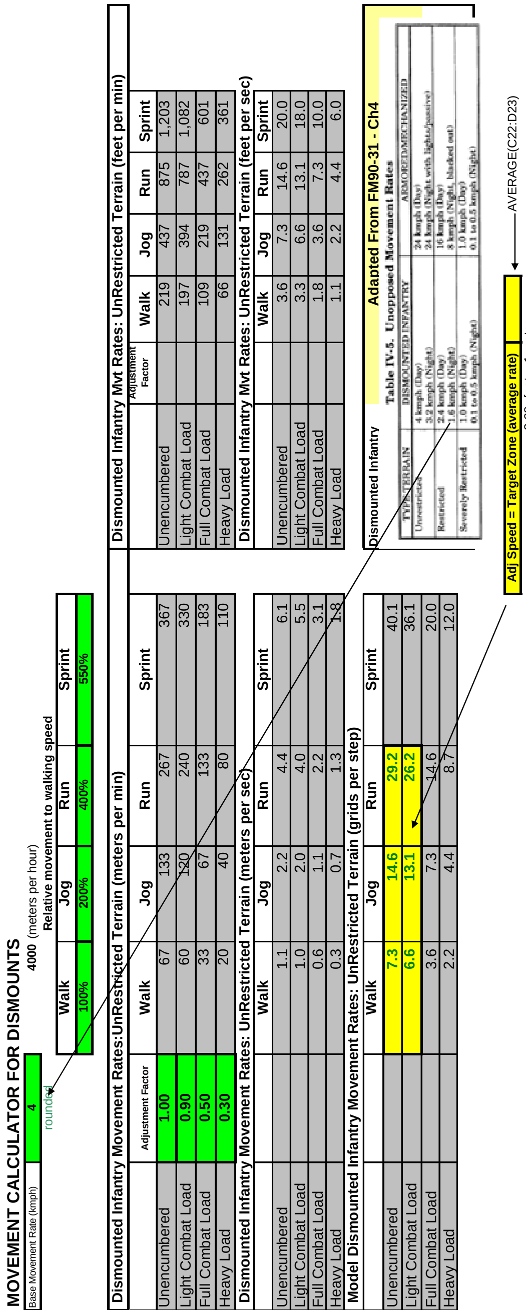
	Agitator (Start)	Agitator Shot 1	Agitator Shot 2	Agitator Shot 3	Agitator Shot 4	Agitator Shot 5	Terrorist Gunman
Agitator (Start)		UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT	NEUTRAL
Agitator Shot 1	UNIT FRIEND		UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	NEUTRAL
Agitator Shot 2	UNIT FRIEND	UNIT FRIEND		UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	NEUTRAL
Agitator Shot 3	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND		UNIT FRIEND	UNIT FRIEND	NEUTRAL
Agitator Shot 4	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND		UNIT FRIEND	NEUTRAL
Agitator Shot 5	UNIT	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND		FRIEND
Civilians	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
Hospital	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
Inner Harbor	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
Central PD	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
SWAT - A1	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
Fire	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
Traffic	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
Terrorist Gunman	UNIT	UNIT	UNIT	UNIT	UNIT	UNIT FRIEND	

	Civilians	Hospital	Inner Harbor	Central PD	SWAT - A1	Fire	Traffic
Agitator (Start)	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND
Agitator Shot 1	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND
Agitator Shot 2	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND
Agitator Shot 3	FRIEND	FRIEND	NEUTRAL	NEUTRAL	NEUTRAL	NEUTRAL	NEUTRAL
Agitator Shot 4	NEUTRAL	FRIEND	NEUTRAL	NEUTRAL	NEUTRAL	NEUTRAL	NEUTRAL
Agitator Shot 5	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
Civilians		FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND
Hospital	FRIEND		FRIEND	FRIEND	FRIEND	FRIEND	FRIEND
Inner Harbor	FRIEND	FRIEND		NEUTRAL	FRIEND	FRIEND	FRIEND
Central PD	FRIEND	FRIEND	FRIEND		FRIEND	FRIEND	FRIEND
SWAT - A1	FRIEND	FRIEND	FRIEND	FRIEND		FRIEND	FRIEND
Fire	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND		FRIEND
Traffic	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND	
Terrorist Gunman	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY

Figure 52. Side Affiliations of Each Agent Class

5. Movement Rates

Figure 53 is a screen shot of an Excel spreadsheet movement calculator adapted from work done by Babilot.[68]



MOVEMENT CALCULATOR FOR DISMOUNTS

Base Movement Rate (kmph)	4	4000 (meters per hour)
	rounded	

Relative movement to walking speed

Walk	Jog	Run	Sprint
100%	200%	400%	550%

Dismounted Infantry Movement Rates:UnRestricted Terrain (meters per min)

	Adjustment Factor	Walk	Jog	Run	Sprint
Unencumbered	1.00	67	133	267	367
Light Combat Load	0.90	60	120	240	330
Full Combat Load	0.50	33	67	133	183
Heavy Load	0.30	20	40	80	110

Dismounted Infantry Movement Rates: UnRestricted Terrain (meters per sec)

		Walk	Jog	Run	Sprint
Unencumbered		1.1	2.2	4.4	6.1
Light Combat Load		1.0	2.0	4.0	5.5
Full Combat Load		0.6	1.1	2.2	3.1
Heavy Load		0.3	0.7	1.3	1.8

Model Dismounted Infantry Movement Rates: UnRestricted Terrain (grids per step)

		Walk	Jog	Run	Sprint
Unencumbered		7.3	14.6	29.2	40.1
Light Combat Load		6.6	13.1	26.2	36.1
Full Combat Load		3.6	7.3	14.6	20.0
Heavy Load		2.2	4.4	8.7	12.0

Dismounted Infantry Mvt Rates: UnRestricted Terrain (feet per min)

	Adjustment Factor	Walk	Jog	Run	Sprint
Unencumbered		219	437	875	1,203
Light Combat Load		197	394	787	1,082
Full Combat Load		109	219	437	601
Heavy Load		66	131	262	361

Dismounted Infantry Mvt Rates: UnRestricted Terrain (feet per sec)

		Walk	Jog	Run	Sprint
Unencumbered		3.6	7.3	14.6	20.0
Light Combat Load		3.3	6.6	13.1	18.0
Full Combat Load		1.8	3.6	7.3	10.0
Heavy Load		1.1	2.2	4.4	6.0

Dismounted Infantry

Adapted From FM90-31 - Ch4

Table IV-5. Unopposed Movement Rates

TYPE TERRAIN	DISMOUNTED INFANTRY	ARMORED/MECHANIZED
Unrestricted	4 kmph (Day) 3.2 kmph (Night)	24 kmph (Day) 24 kmph (Night with lights/passive)
Restricted	2.4 kmph (Day) 1.6 kmph (Night)	16 kmph (Day) 8 kmph (Night, blacked out)
Severely Restricted	1.0 kmph (Day) 0.1 to 0.5 kmph (Night)	1.0 kmph (Day) 0.1 to 0.5 kmph (Night)

Adj Speed = Target Zone (average rate) ← AVERAGE(C22:D23)

3.28 feet = 1 meter

Figure 53. Excel Movement Rate Calculator

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[68]Michael Babilot, "Comparison of a Distributed Operations Force to a Traditional Force in Urban Combat," Masters Thesis, Naval Postgraduate School, Monterey, CA, September 2005.

This appendix served to answer questions the reader may have had about the numbers used to develop this simulation by describing where the data came from and how the numbers were developed.

APPENDIX B – EXPERIMENTAL DESIGN METHODOLOGY

This appendix provides additional detail about the procedures used to develop the experimental designs for this research. It expands upon the discussion of OLHs, NOLHs, and FRLHs, to provide more information on how the number of experimental design points is calculated for a given simulation. In addition, this appendix provides the Visual Basic code that can form the bridge between any Latin Hypercube builder and study file for Pythagoras or MANA.

A. DESIGN POINT CALCULATIONS

1. Design by Ye

Figure 54 shows the relationship between number of variables and required levels to maintain orthogonality of design points, as determined by Ye.

Step 1: Determine number of variables (k)
Step 2: Calculate $m = \frac{k+2}{2}$
Step 3: Calcuate number of required levels $n = 2^m + 1$

Figure 54. Relationship of *k, m,* and *n*, as determined by Ye

2. Design by Cioppa

Table 23 illustrates a finding by Cioppa that

> . . . as the number of levels doubles (less one for the center point), Ye's [Orthogonal Latin Hypercube] OLHC designs are able to accommodate exactly two more variables.[69] In the new designs [by Cioppa], the corresponding maximum number of variables increases in accordance with the following formula.[70]

[69]K.Q. Ye, "Orthogonal Column Latin Hypercubes and their Application in Computer Experiments," *Journal of the American Statistical Association – Theory and Methods*, Vol. 94, No. 144, pp. 1430-1439, December 1998.

[70]Thomas M. Cioppa, "Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models," Ph.D. Dissertation, Operations Research Department, Naval Postgraduate School, Monterey, CA, 2002.

$$k = m + \binom{m-1}{2}$$

Figure 55. Determination of Maximum Variables for Given Number of Design Points (Cioppa)

Total Number of Levels for Each Variable (n)	m	Maximum Number of Variables Using Cioppa's Design (k)	Maximum Number of Variables Using Ye's Design
17	4	7	6
33	5	11	8
65	6	16	10
129	7	22	12

Table 22. A Comparison Illustrating the Increased Number of Variables that can be Examined by Extending Ye's (1998) Construction Algorithm for OLHCs

3. Design by Hernandez

Hernandez[71] found that that as the number of levels increases, the possible number of variables that can be explored increases to no more than one-third the number of levels. Hernandez found that using correlation reductin methods, it is possible to create a design that meets Cioppa's NOLH criteria, when the number of design points is greater than or equal to 49 (see Figure 56).

n := number of design points (levels)
k := number of variables

When $n \geq 49$,
$$n \geq 3k$$

Figure 56. Relationship Between Number of Variables and Number of Levels in Hernandez's Design of Experiments

[71] Alejandro D. Hernandez, "Expanding the Family of Efficient, High-Dimensional, Nearly Orthogonal Experimental Designs through Flexible Random Latin Hypercubes Methods," Ph.D. Dissertation, Operations Research Department, Naval Postgraduate School, Monterey, CA, pending publication.

Table 24 highlights the difference between Cioppa's design and Hernandez's design in the number of possible variable analyzed in a given number of possible design points.

Total Number of Levels for Each Variable (n)	m	Maximum Number of Variables Using Hernandez's Design (k)	Maximum Number of Variables Using Cioppa's Design
129	7	43	22
257	8	85	29
513	9	171	37
1,025	10	341	46
2,049	11	683	56

Table 23. A Comparison Illustrating the Increased Number of Variables that can be Examined by Extending Cioppa's Construction Algorithm for NOLHs

B. EXCEL MACRO BY MICHEL

Figure 57 is Visual Basic code, developed by Major Christopher Michel, USMC.[72] This code was developed to run in Microsoft Excel; it converts a Latin Hypercube into a format that easily imported into a study file to execute a data farming experiment in either Pythagoras or MANA.

[72] Christopher Michel, "Supporting A Marine Air Ground Task Force With Appropriate Quantities of Ground Based Fire Support," Masters Thesis, Naval Postgraduate School, Monterey, CA, September 2006.

```
Sub TransposeNumberMacro()
'
' TransposeNumberMacro Macro
' Macro recorded 3/27/2006 by localadmincm
'

'Ensure data starts in 2nd column to use this code
xX = 0

    For DesignPoint = 0 To 144

        For j = 1 To 48 'factors
            Sheets("YOUR_LATIN_HYPERCUBE_GOES_HERE").Select
            Cells(2 + DesignPoint, j + 1).Copy
            Sheets("VBA for XML").Select
            Cells(xX + j + 1, 2).Select
            ActiveSheet.Paste
            Application.CutCopyMode = False

        Next j

        xX = xX + 50 'transposes data

    Next DesignPoint
End Sub
```

Figure 57. Excel Macro by Michel

APPENDIX C – DATA ANALYSIS

This appendix provides an illustration of the Clementine stream used to clean the data resulting from the simulation runs conducted.

A. LARGE FRLH EXPERIMENT

Figure 58 Illustrates the process by which Clementine can be used to transform the data received from a Pythagoras submission to MHPCC into a data set that contains exactly the information required for analysis.

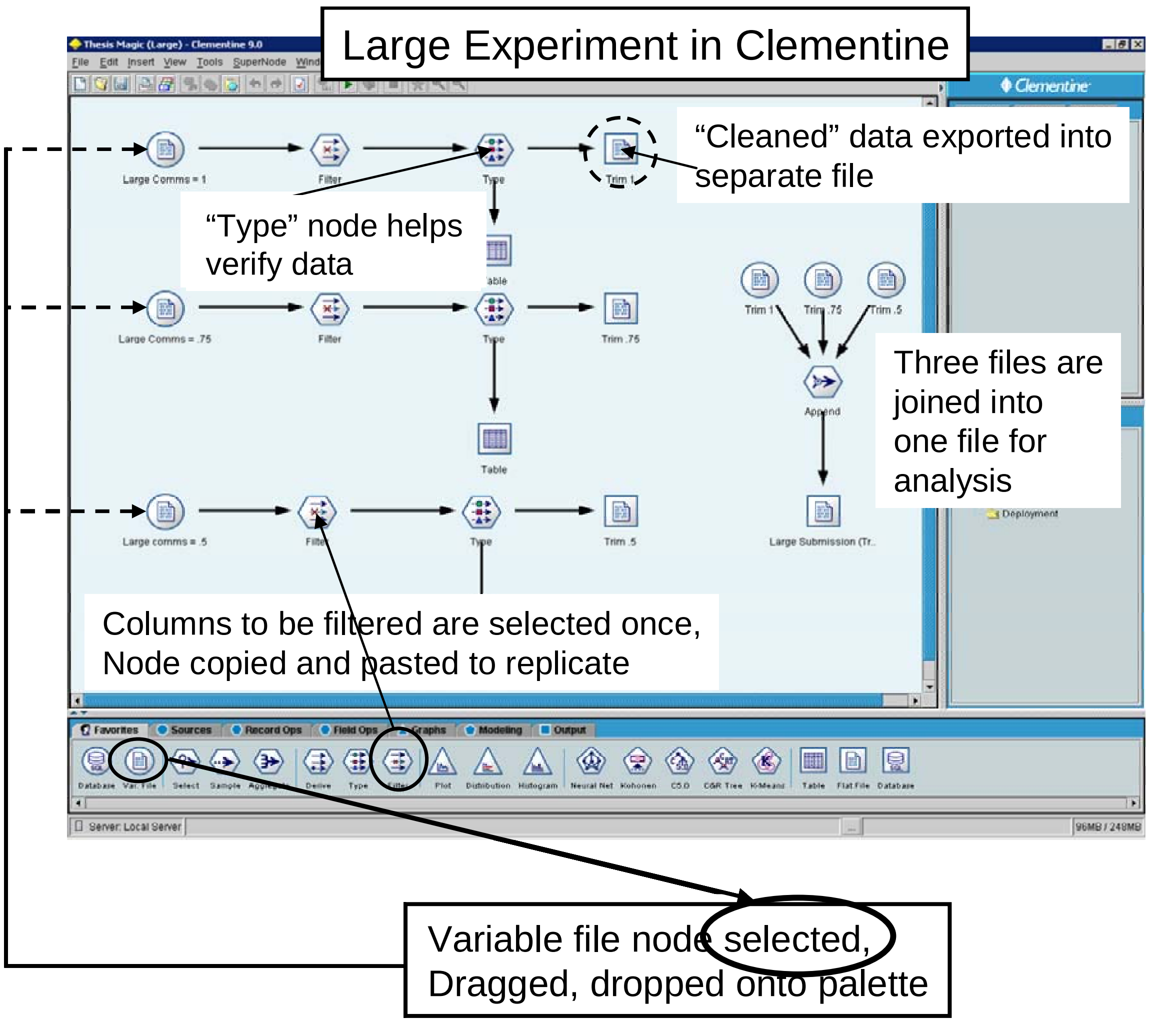

Figure 58. Using Clementine to Clean Large FRLH Data

B. SMALL FRLH EXPERIMENT

The same Clementine stream is used to clean the small data set as was used for the large. The input files are simply deleted, and the files corresponding to the small FRLH data are uploaded.

C. GRIDDED EXPERIMENT

The gridded experiment required the same approach to the FRLH experiments, but required the addition of two additional file inputs. The existing streams were simply copied and pasted; it was not necessary to build them from the start.

APPENDIX D – PAIW-12 FINDINGS

This appendix provides information about findings that resulted from the PAIW-12 workshop, held in Boppard, Germany, from June 1-10, 2006. The work of PAIW-12 Syndicate 2 was a follow on work from the research presented in this document. Syndicate 2 was composed of the following people:

- Major Jonathan W. Roginski, United States Army
- Ms. Gudrun Wagner, Germany, European Aeronautic Defence and Space (EADS) Systems, Defence and Security
- Mr. Ole Jakob Sendstad, Norway, Norwegian Defence Research Establishment

The overall goal of the workshop for Syndicate 2 was to model pro and anti first responder civilians, and the effect of neutral civilians adopting an allegiance of either pro or anti first response, while decreasing simulation run time. The syndicate used the following MOEs to evaluate first responder success; all statistics were collected at the end of the simulation run.

- Percentage of civilians killed or injured
- Percentage of civilians near the triage point

Figure 59 is an overview of what was accomplished during the week.

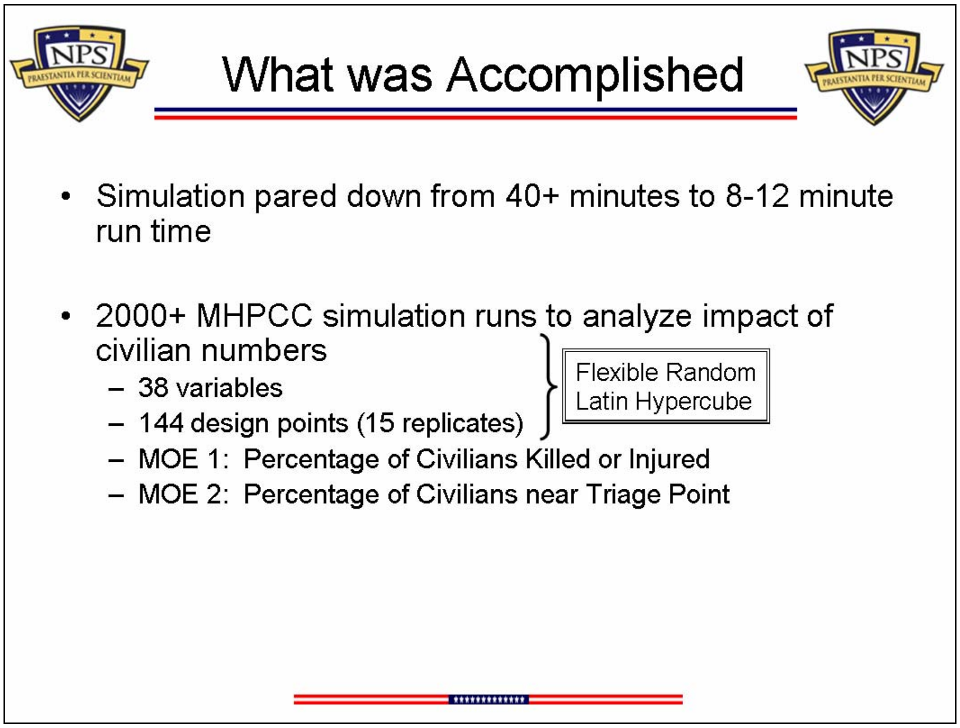

Figure 59. PAIW-12 Accomplishments

The syndicate was able to complete the modeling of pro and anti response civilians, in addition to neutral civilian transitions in less than one week, but was not able to have the data set returned from MHPCC in time to analyze before the close of the workshop.

A. MOE 1

The syndicate did receive the base case scenario submission in time for analysis, resulting in some interesting results. Figure 60 is an illustration of analysis results that focused on MOE 1 from Figure 59.

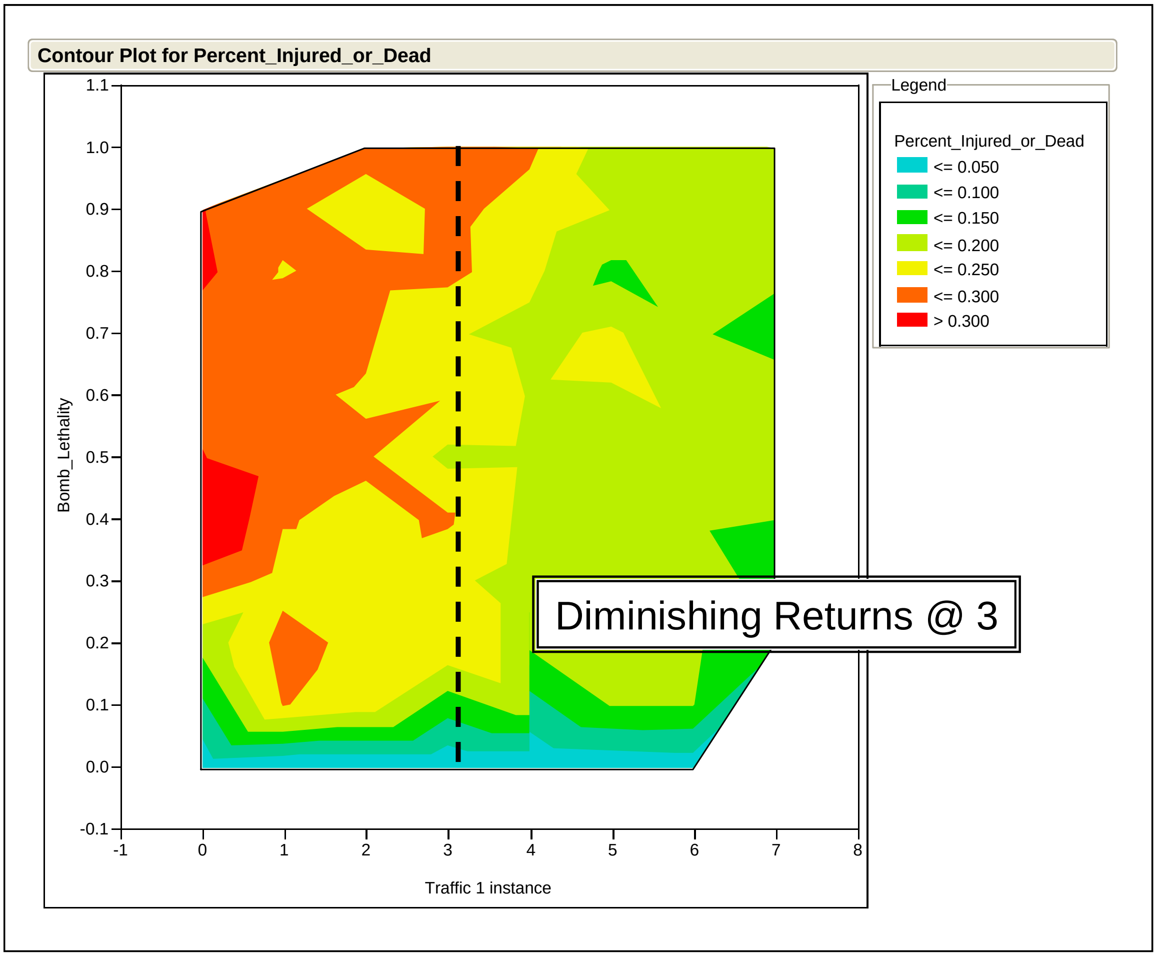

Figure 60. MOE 1 Results

The CART diagram (not shown) indicated that the two most important variables in determining the percentage of civilians killed or injured were the number of police at intersection 1 (northwest corner) and the lethality of the bomb. The contour plot in Figure 60 plots the two most important variables on the horizontal and vertical axes and uses color to emphasize the response variable: civilians injured or killed.

Analysis of MOE 1 seems to indicate that, while the number of police at this location is important, more is not always better. In this simulation, there appears to be diminishing returns after three police arrive at the location; there is little increase in the MOE with additional police at the location. Although a low resolution simulation cannot be trusted to determine that the number 3 is exactly the correct number at which the diminishing returns happens, it can be an indicator that the point of diminishing returns exists and that the decision maker should be aware of it.

B. MOE 2

Using a similar technique to that used for MOE 1, the syndicate first used a CART diagram to identify the most important variables. For this MOE, the most important variables were the lethality of the bomb, and the number of police that patrol the middle patrol area. The contour plot in Figure 61 plots the two most important variables on the horizontal and vertical axes and uses color to emphasize the response variable: civilians injured or killed.

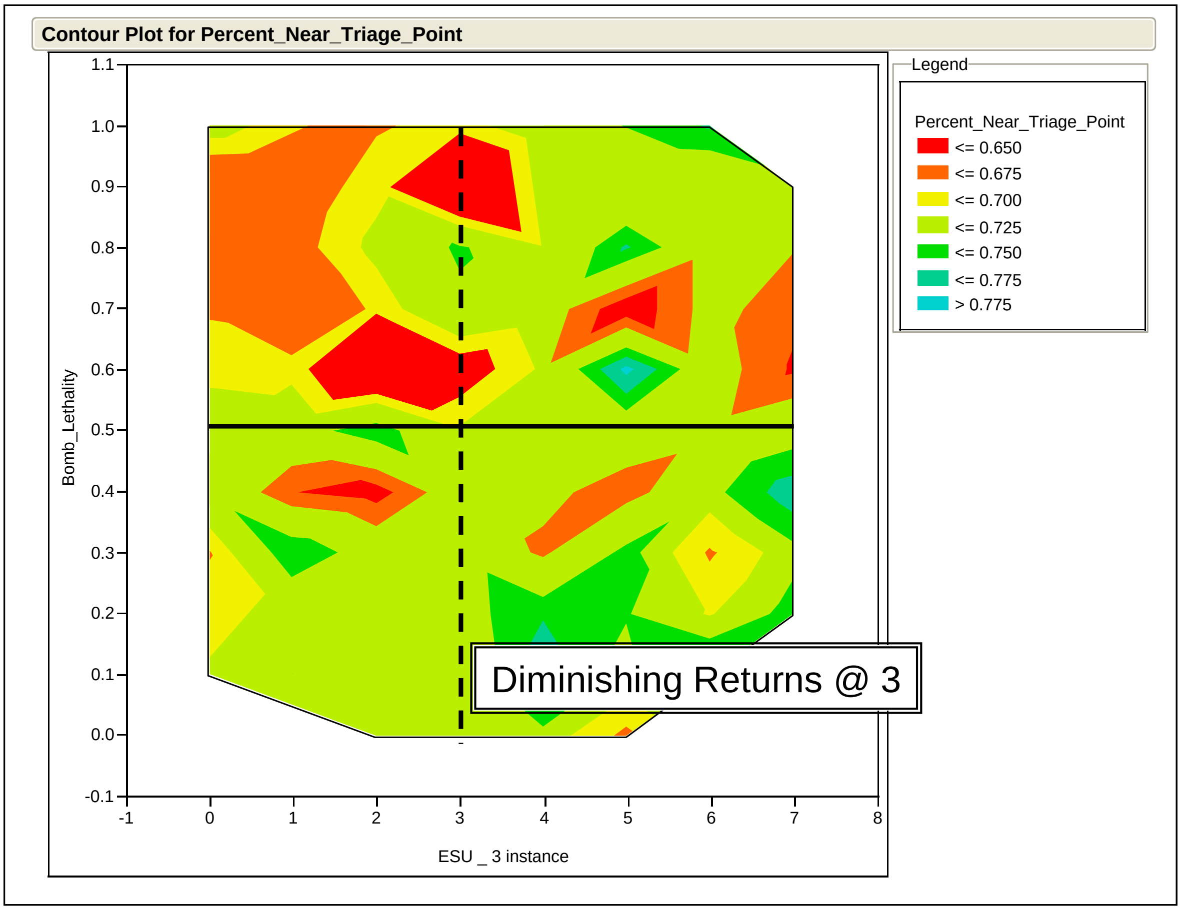

Figure 61. MOE 2 Results

Analysis of MOE 1 seems to indicate a similar diminishing return in the central patrol area as was indicated at the northwest intersection in MOE 1, although the relationship is not as strong.

Overall, analysis of the data resulting from PAIW-12 suggests:

- It is possible to create the forces in an emergency response simulation, debug the scenario, and use data farming techniques to receive data to analyze within one week.
- There may be an optimal number of traffic police per intersection and patrolmen per area. Exceeding that number could result in diminishing returns, or an inefficient use of manpower.

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